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U.S. Department of Energy

DUF_6 MATERIALS USE ROADMAP

September 1, 2000

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PREFACE

A paper copy of the roadmap can be obtained by sending a fax with the requestor's name and address to (301) 903-4905 or sending a card or letter to

> Depleted Uranium Hexafluoride Management Program (NE-30)
> U.S. Department of Energy
> 19901 Germantown Road
> Germantown, MD 20874

Comments on the roadmap can be submitted by

- fax using the number above,
- paper copy using the address above, or
- electronic mail to DUF6.comments@hq.doe.gov using "Comments on DU Uses Roadmap" as the subject line.

Comments must be received by October 20, 2000, to be considered for incorporation into the final roadmap.

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EXECUTIVE SUMMARY

The U.S. government has approximately 700,000 metric tons (MT) of surplus depleted uranium (DU) in various chemical forms stored at Department of Energy (DOE) sites across the United States. This material, most of which is DU hexafluoride (DUF_6) resulting from uranium enrichment operations but which also includes other surplus DU, is the largest amount of nuclear material in DOE's inventory. On July 6, 1999, DOE issued the *Final Plan for the Conversion of Depleted Uranium Hexafluoride as required by Public Law 105-204,* in which DOE committed to develop a *Depleted Uranium Hexafluoride Materials Use Roadmap* in order to establish a strategy for the products resulting from conversion of DUF_6 to a stable form. This report meets the commitment in the Final Plan by providing a comprehensive roadmap that DOE will use to guide any future research and development (R&D) activities for the materials associated with its DUF_6 inventory. This roadmap supports the decision presented in the *Record of Decision for Long-Term Management and Use of Depleted Uranium Hexafluoride*, namely to begin conversion of the DUF_6 inventory as soon as possible, either to uranium oxide, uranium metal, or a combination of both, while allowing for future uses of as much of this inventory as possible. In particular, this roadmap is intended to explore potential uses for the DUF_6 conversion products and to identify areas where further development work is needed. The roadmap focuses on potential governmental uses of DUF_6 conversion products but also incorporates limited analysis of using the products in the private sector. This roadmap is one of a number of DOE documents that support DOE's Environmental Quality Portfolio, and it builds on the analyses summarized in the recent *Programmatic Environmental Impact Statement for Alternative Strategies for the Long-Term Management and Use of Depleted Uranium Hexafluoride*. This roadmap also addresses other surplus DU, primarily in the form of DU trioxide and DU tetrafluoride.

The DU-related inventory considered in this roadmap includes the following:

- Components directly associated with the DUF_6 presently being stored at gaseous diffusion plant sites in Paducah, Kentucky, Portsmouth, Ohio, and Oak Ridge, Tennessee
  - 470,000 MT of DU
  - 225,000 MT of fluorine chemically combined with the depleted uranium
  - 74,000 MT of carbon steel comprising the storage cylinders[1]

- 25,500 MT of DU, primarily in the form of uranium trioxide and tetrafluoride, containing varying amounts of radioactive and chemical impurities, presently stored primarily at DOE's Savannah River Site.

The inventory includes consideration of a national resource reserve but excludes DU required for use by ongoing programs.

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[1]Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.

This roadmap characterizes and analyzes alternative paths for eventual disposition[2] of these materials, identifies the barriers that exist to implementing the paths, and makes recommendations concerning the activities that should be undertaken to overcome the barriers. The disposition paths considered in this roadmap are shown in Fig. ES.1. Most paths consider the potential beneficial use of the DU and other DUF_6 conversion products for the purpose of achieving overall benefits, including cost savings to the Federal government, compared with simply disposing of the materials. However, the paths provide for assured direct disposal of these products unless cost-effective and institutionally feasible beneficial uses are found. While it is likely that implementation of DOE's approach to disposition of DU-related materials will show some of these paths to be unworthy of further pursuit or deployment, it is expected that paths will remain which can significantly reduce cost and improve operations while offering private-sector employment opportunities related to the manufacture of useful products.

The general disposition paths that DOE envisions for DU-related materials are (a) implementation of cost-effective and institutionally feasible beneficial uses of DU using the products of DUF_6 conversion and other forms of DU in DOE's inventory, (b) processing the fluorine product resulting from DUF_6 conversion to yield an optimal mix of valuable fluorine compounds (*e.g.*, hydrofluoric acid, boron trifluoride) for industrial use, and (c) processing emptied cylinders to yield intact cylinders that are suitable for reuse, while maintaining an assured and cost-effective direct disposal path for all of the DU-related materials.[3]

Many of the paths included in this roadmap, particularly those that could lead to beneficial use of DUF_6 conversion products, face technical or institutional barriers, and significant uncertainties surround projections of cost-reduction benefits and operational improvements. Therefore, DOE has identified barrier reduction activities supporting beneficial use of DU conversion products while also making appropriate investments to ensure that disposal alternatives are available. A summary of the Department's approach is described in the following paragraphs.

First, DOE will support a broad spectrum of investments to reduce the barriers to paths related to nuclear material storage and/or disposal that have relatively low technical risk and use large quantities of DU in regulated areas.

Second, DOE will support targeted investments to reduce barriers for a number of paths where there is potential to use substantial amounts of DUF_6 conversion products or other forms of DU, but where the uses are more speculative or simply require a small investment before the path could be followed.

Third, DOE will make appropriate investments to ensure that there are no barriers to following an optimal path for long-term storage or direct disposal of the DU conversion products that are not beneficially used, or to disposal of DU-bearing products at the end of their useful lives.

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[2]Disposition constitutes some combination of long-term storage, beneficial use, and eventual disposal.

[3]Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.

Fourth, DOE will invest in basic and mission-directed research that is related to beneficial use of DUF_6 conversion products. These investigations are necessary to provide a basis for evaluating the feasibility, impacts, and economics of potential DU disposition paths and to identify new beneficial uses of the DU conversion products.

Fifth, DOE will invest in system analysis and support activities that cross-cut multiple DUF_6 conversion products and other forms of DU. These activities include establishing roles and responsibilities for disposition of these products, efforts to foster acceptance of useful DU-bearing products and materials, and system baseline and optimization.

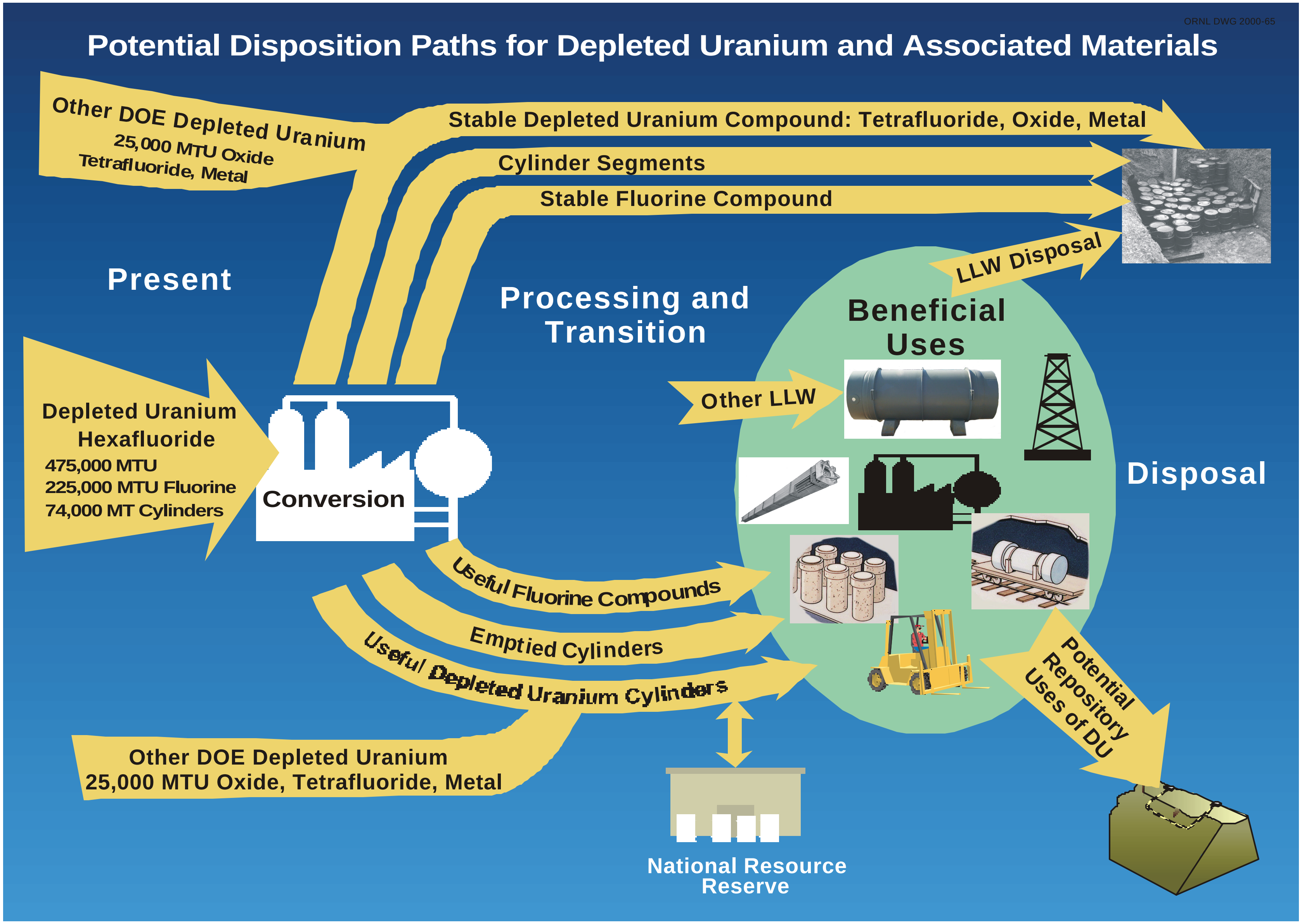

Fig. 3.1 Paths for disposition of surplus depleted uranium. Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.

1. INTRODUCTION

The U.S. government has approximately 700,000 metric tons (MT) of surplus depleted uranium (DU) in various chemical forms stored at Department of Energy (DOE) sites across the United States. This material, most of which is DU hexafluoride (DUF_6) resulting from uranium enrichment operations but which also includes other surplus DU, is the largest amount of nuclear material in DOE's inventory. On July 6, 1999, DOE issued the *Final Plan for the Conversion of Depleted Uranium Hexafluoride as required by Public Law 105-204* [DOE 1999b], in which DOE committed to develop a *Depleted Uranium Hexafluoride Materials Use Roadmap* in order to establish a strategy for the products resulting from conversion of DUF_6 to a stable form. This report meets the commitment in the Final Plan by providing a comprehensive roadmap that DOE will use to guide any future research and development (R&D) activities for the materials associated with its DUF_6 inventory. This roadmap supports the decision presented in the *Record of Decision for Long-Term Management and Use of Depleted Uranium Hexafluoride* [FR 1999], namely to begin conversion of the DUF_6 inventory as soon as possible, either to uranium oxide, uranium metal, or a combination of both, while allowing for future uses of as much of this inventory as possible. In particular, this roadmap is intended to explore potential uses for the DUF_6 conversion products and to identify areas where further development work is needed. The roadmap focuses on potential Governmental uses of DUF_6 conversion products but also incorporates limited analysis of using the products in the private sector.[1] This roadmap is one of a number of DOE documents that support DOE's Environmental Quality Portfolio [DOE 1999c], and it builds on the analyses summarized in the recent *Programmatic Environmental Impact Statement for Alternative Strategies for the Long-Term Management and Use of Depleted Uranium Hexafluoride* [DOE 1999a] and documented in engineering [Dubrin 1997] and cost [Elayat 1997] analysis reports. This roadmap also addresses other surplus DU, primarily in the form of DU trioxide and DU tetrafluoride.

1.1 Roadmapping Process

The process of defining and characterizing DOE's surplus DU inventory, specifying the alternative paths that could result in disposition of the DU, evaluating the paths, and recommending the preferred paths and activities required to overcome barriers along the paths is called *roadmapping*. The process steps involved in roadmapping DU and documented in this report are summarized as follows:

- <u>Define the DU materials to be considered</u>: The scope of the roadmap in terms of the range of DU materials considered is discussed in Sect. 1.2. Within this scope, the general disposition paths for DOE's surplus DU and the materials associated with it are described in Sect. 1.3.

- <u>Characterize the present state of the DU inventory</u>: Section 2 summarizes the characteristics of the relevant DU materials, including the following:
  - The inventory of DU, fluorine, and cylinders
  - Important characteristics of the inventory such as chemical form, contaminant concentrations, and enrichments
  - The regulatory context of the inventory and potential use of DU

[1] Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.

- Specify and analyze alternative disposition paths. Section 3 summarizes the paths that are considered and characterizes each of them with respect to the following factors:
  - Existence of barriers to be overcome along the path
  - Amount of the inventory that could be used
  - Technical maturity and barriers
  - Institutional (including regulatory, legal, and policy) status and barriers
  - Economic and market aspects
  - Other impacts (*e.g.*, changes in risk or environmental effects)

- Evaluate and categorize the paths: Section 4 summarizes the approach to and results of evaluating the DU disposition paths against criteria based on the characterization factors listed immediately above. The paths were evaluated by the following process:
  - Convening a workshop to review the information available concerning the paths
  - Having a group of knowledgeable scientists, engineers, and DOE staff members individually rank the paths
  - Summarizing and discussing the rankings to the point of consensus
  - Assigning each path to one of four categories:
    A. Further barrier-reduction activities recommended
    B. Further barrier-reduction activities should be considered
    C. Further barrier-reduction activities should not be considered
    D. No additional Federal barrier-reduction activities required to support DU disposition

- Specify DU disposition barrier-reduction activities for each path: Section 5 summarizes the barrier-reduction activities for each path in the following categories:
  - Recommended path-specific activities
  - Activities that should be considered
  - Recommended cross-cutting and systems activities
  - Recommended topics for DOE research programs

- Define DOE's path forward regarding DU disposition: Using the results of Sect. 5 as a basis, Sect. 6 summarizes a five-point plan that constitutes DOE's preferred approach for overcoming the barriers to DU disposition. It is this plan that DOE intends to follow, subject to budget limitations.

1.2 Roadmap Scope

The materials considered in this roadmap are all DOE surplus DU or related materials, including fluorine and emptied storage cylinders associated with DUF_6. Consideration of establishing a national resource reserve is also included but DU required for ongoing programs such as those in DOE's National Nuclear Security Agency (DOE-NNSA) or Department of Defense (DoD) is excluded.

The range of alternative DU disposition paths considered is as follows:

- Begin with these materials:
  - The products from conversion of DUF_6
  - Non-DUF_6 forms of surplus DU in DOE's inventory

- Explore beneficial uses of DU, fluorine by-products, and emptied cylinders[2] while maintaining the option to directly dispose of some or all of these conversion products. The beneficial uses considered will emphasize potential Federal applications with some consideration being given to potential non-Federal applications.

- End with disposal of the DU-bearing products as an integral part of use or at the end of their useful life.

1.3 General Depleted Uranium Disposition Paths

The general disposition paths that DOE envisions for DU-related materials are (a) implementation of cost-effective and institutionally feasible beneficial uses of DU using the products of DUF_6 conversion and other forms of DU in DOE's inventory, (b) processing the fluorine product resulting from DUF_6 conversion to yield an optimal mix of valuable fluorine compounds (*e.g.*, hydrofluoric acid, boron trifluoride) for industrial use, and (c) processing emptied cylinders to yield intact cylinders that are suitable for reuse,[2] while maintaining an assured and cost-effective direct disposal path for all of the DU-related materials.

[2]Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.

2. CURRENT INVENTORY AND CHARACTERISTICS OF DEPLETED URANIUM AND ASSOCIATED FLUORINE AND CYLINDERS

This section provides foundational information for the rest of the DU disposition roadmap. First, Sect. 2.1 defines the inventory and characteristics of DU, fluorine, and cylinders that are within the scope of this roadmapping effort, including the form and location of the inventory. Sections 2.2–2.4 provide general background information on regulations relevant to the disposition of this inventory.

2.1 Inventory of Depleted Uranium and Associated Materials

2.1.1 Depleted Uranium. Depleted uranium—uranium with ^{235}U content less than the naturally occurring concentration of 0.711 wt % — has been generated in the United States as tailings from uranium enrichment operations. This study will address technology associated with management and disposition of purified forms of DU. It focuses on the DU hexafluoride (DUF_6) that constitutes the majority of the inventory but includes the relatively small quantities of DU that resulted from purification of products from fuel reprocessing operations at Hanford and Savannah River.

The entire U.S. inventory of purified DU that has been generated as tails from uranium enrichment and spent fuel reprocessing is approximately 500,000 metric tons of elemental uranium (MTU) and is summarized in Table 2.1. About 470,000 MTU of DU, managed by DOE's Office of Nuclear Energy, Science, and Technology (DOE-NE), is stored as UF_6 in cylinders at the three U.S. gaseous diffusion enrichment sites—Paducah, Kentucky; Portsmouth, Ohio; and Oak Ridge, Tennessee. Approximately 25,500 MTU, managed by DOE's Office of Environmental Management (DOE-EM), exists at various sites in a number of chemical forms, including oxides, tetrafluoride, metal, alloys, and process residues. Another approximately 2500 MTU that is managed by DOE-NNSA, DoD, and U.S Nuclear Regulatory Commission (NRC) licensees is excluded from consideration because it is intended for use by these organizations.

<u>2.1.1.1 Uranium Hexafluoride</u>. The U.S. uranium enrichment plants have been operated since the mid-1940s, resulting in the continuous production of DUF_6. However, they have been operated under varying policy and economic conditions and with different feed materials. As a result, the stored DUF_6 has a range of characteristics important to DU disposition. In particular, the following characteristics are noted:

- The ^{235}U content of the DUF_6 (*i.e.*, the extent to which the uranium was depleted in ^{235}U during enrichment) varies from less than 0.2% to nearly the levels in natural uranium (0.711%). However, the average enrichment is about 0.27%, and 91% of the tails have an enrichment less than 0.4%.

- At times the uranium enrichment plants were fed with recycled uranium that contained trace amounts of radionuclides such as ^{237}Np and ^{99}Tc that form volatile fluoride compounds. As a result, there are traces of these radionuclides in some DUF_6 cylinders.

- The DUF_6 placed in the storage cylinders is a radioactive material. As a result, radioactive decay products have built up in the storage cylinders over the years. The consequence of this is that the DU decay products in the emptied cylinders will be about 20 times more radioactive than the DU removed from the cylinders, and the radioactivity of products made from DU will also increase by 20-fold with a few years after manufacture. The dose rate 30 cm from a large unshielded mass of DU is 1.5 – 2.0 mrem/hr.

2.1.1.2 Uranium Trioxide (UO_3). DOE-EM currently manages about 23,400 MT UO_3 containing about 19,500 MTU as DU trioxide (DUO_3), resulting from historical weapons production programs at the U.S. defense complexes. Depleted UO_3, recovered either through chemical separation procedures used in ^{239}Pu production programs or as a by-product from target and weapons component fabrication, is now stored at the Fernald Environmental Management Project (FEMP) and the Savannah River Site (SRS). The UO_3 at FEMP is in process of being transferred to DOE-NE at Portsmouth.

2.1.1.3 Uranium Metal. Most of the approximately 3000 kg of DOE-EM-managed DU metal, located primarily at FEMP, is in the form of ingots or "derbies," typically 12-inch diameter by 8 inch long, with a density of 19.05 kg/liter. The derbies are the raw material for producing finished products, including coated metal and alloys. This material is in the process of being transferred to DOE-NE management at Portsmouth.

2.1.1.4 Uranium Tetrafluoride (UF_4). The DOE-EM-managed UF_4 was produced, primarily at FEMP, as a step in the production of uranium metal. This material is in the process of being transferred to DOE-NE management at Portsmouth. Discussions are currently in progress to document possible DoD interest in this UF_4.

2.1.1.5 Other Forms. Other DOE-EM-managed materials, including miscellaneous oxides, solutions, and process residues may need to be converted and packaged for disposition.

2.1.2 Fluorine. Approximately 225,000 MT of elemental fluorine could be derived from the approximately 700,000 MT of DUF_6 stored at the DOE enrichment sites. This fluorine is potentially recoverable as elemental fluorine, hydrofluoric acid (aqueous HF), anhydrous HF, or other fluorine-bearing compounds. These could be recycled to conserve natural resources and partially defray costs associated with conversion of DUF_6 to forms that are more acceptable for storage. The HF products can be used in many commercial industrial activities, particularly in the nuclear industry to fluorinate natural uranium.

2.1.3 UF_6 Cylinders. The number and types of DUF_6 cylinders at the three enrichment sites were determined by the Bechtel Jacobs Company in May 1999 [Manual 1999], and detailed properties of the various models of DUF_6 cylinders were obtained from the U.S. Enrichment Corporation (USEC) [USEC 1999]. Greater than 99.92% of the total cylinder mass of approximately 74,000 MT is composed of formed and welded ASTM A516 or A285 carbon steel plates [DNFSB 1995]. The steel cylinders have nominal wall thickness of 0.313 inch; the minium thickness considered for safe handling and transportation is 0.25 inch. Cylinders presently considered acceptable for UF_6 handling and shipment must be inspected, tested, and maintained within the intent of the standard ANSI N14.1. Old or corroded cylinders not meeting the ANSI standard require special handling—features such as special overpacks, transfer of contents to approved cylinders, and approval for exception by regulatory agencies such as the U.S. Department of Transportation (DOT).

In addition to the steel cylinders, there are nickel and Monel cylinders. A total of 49 MT of nickel and 9 MT of Monel comprising 779 small cylinders will become available as a result of DUF_6 disposition.

Intact cylinders of uranium enrichment tailings normally contain DUF_6 with purity exceeding 99.9%. Aged, intact cylinders have small quantities of other uranium fluorides (*e.g.*, DUF_5), fluorides of uranium decay products, and fluorides of container-corrosion products. Previously breached cylinders may contain hydrous oxides, including uranium oxyfluoride generated by reaction of the DUF_6 with moist air. Tailings may also contain small quantities of the radioisotope ^{237}Np, a residual from the use of "reactor recycle" cascade feed. All of these impurities generally remain as a solid residue, or "heel," in the cylinder when the DUF_6 is removed by liquefaction or vaporization [Michelhaugh, 1999]. Cylinders previously containing DUF_6 generally exceed radiation and chemical hazard standards for unrestricted use unless they have been decontaminated and inspected. Most management strategies will require that emptied cylinders be cleaned to remove the solid residues and any remaining DUF_6.

2.2 Current Regulatory Status of Depleted Uranium and Associated Materials

All paths to disposition of DU discussed in this report are composed of one or more of the following activities involving DU: storage; transfer; processing (*e.g.*, conversion, fabrication); product use; and disposal. The regulations applicable to an activity will depend largely on whether, within a particular path, the activity is controlled by DOE or is regulated instead by the NRC or an NRC Agreement State. This section summarizes the current regulatory status of DU, and for each of the five activities, summarizes existing regulatory requirements and issues relevant to the roadmapping effort.

2.2.1 Regulatory Status of Depleted Uranium. Under the Atomic Energy Act of 1954 (AEA)[PL 1954], as amended, the purified chemical forms of DU contained in DOE's inventory are classified as "source material." As such, DOE's DU is excluded from the definitions of solid and hazardous waste in the Resource Conservation and Recovery Act (RCRA) [RCRA 1976]. This means that RCRA should not apply to DU activities within any path, unless the purified DU becomes mixed with some other material to which hazardous waste provisions of RCRA do apply.

Under the definitions of radioactive wastes contained in the Nuclear Waste Policy Act of 1982 (NWPA), the Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPAA), and the Waste Isolation Pilot Project Land Withdrawal Act of 1992, DU is low-level waste (LLW) when disposed of. In general, materials contaminated with significant residual DU (*e.g.*, empty DUF_6 cylinders and discarded CaF_2 from the neutralization of gas waste streams) are also low-level radioactive waste when disposed of.

2.2.2 Requirements and Issues Related to Storage. DOE has entered into agreed orders with the responsible regulatory agencies in Ohio and Tennessee regarding ongoing storage of DUF_6. DOE intends to comply with the requirements of these agreed orders. Therefore, the orders should not affect future regulation of DU storage. DOE will conduct appropriate site-specific reviews, as required by the National Environmental Policy Act of 1969 (NEPA), for DU oxide or metal storage at any new or existing DOE-controlled site or non-DOE facility. If storage facilities which are not exempt from the requirement to be licensed are used, DOE must ensure that such facilities are authorized by valid NRC or NRC Agreement State licenses (DOE M 474.1-2).

2.2.3 Requirements and Issues Related to Transfers

2.2.3.1 Depleted Uranium. A DOE-controlled DUF_6 facility is generally allowed to transfer DU, regardless of form, only to authorized DOE-controlled facilities or non-DOE facilities with appropriate NRC or NRC Agreement State licenses (DOE M 474.1). In some cases the impurities in the DU may not be acceptable under existing licenses for some non-DOE facilities, and changes would be required before the DU could be accepted.

2.2.3.2 Residual Radioactive Material in Fluorine Products. DOE has established no generic release limits for the transfer from DOE control of fluorine products containing volumetrically distributed residual radioactivity. Therefore, case-specific release limits developed and approved by DOE according to the process explained in the *Draft Handbook for Controlling Release for Reuse or Recycle of Non-Real Property Containing Residual Radioactive Material* [DOE 1997] would be needed before releasing such material from a DOE-controlled DU conversion facility. Among other things, such release limits must ensure against releasing a licensable quantity of uranium to any person not licensed to receive it. Uranium becomes licensable by the NRC in a mixture or solution (such as a fluorine by-product) at a concentration greater than or equal to 0.05 wt % (500 ppm by weight) [10 CFR 40.13(a)]. It is anticipated that the uranium concentration in fluorine products will be much less than 500 ppm.

2.2.3.3 Residual Radioactive Material in Empty DUF_6 Cylinders. If a DOE-controlled DUF_6 conversion facility releases empty DUF_6 cylinders to a non-DOE metal-recycling facility, the recycling facility must hold an NRC or Agreement State license. Earlier this year, in response to concerns about the release of volumetrically contaminated nickel from the East Tennessee Technology Park, the Secretary of Energy established a moratorium prohibiting the release of all volumetrically contaminated metals from DOE facilities to give the NRC time to develop national standards for volumetrically contaminated materials, allow the public to weigh in on the development of a national policy, and allow DOE to establish its moratorium policy, directives, and guidance in this regard. In addition, on July 13, 2000, DOE Secretary Richardson suspended the unrestricted release for recycling of scrap metals from radiation areas within DOE facilities. This suspension is to remain in effect until DOE implements improved release criteria and information management requirements relating to these materials. The impact of these activities and decisions on potential use of fluorine products years hence is unknown.

2.2.4 Requirements and Issues Related to Processing. Facilities that are not operated for or on the account of DOE that fabricate DU products must hold an NRC or NRC Agreement State specific source material licenses issued under 10 CFR Part 40, "Domestic Licensing of Source Material." If such a facility fabricates and distributes products or devices that will be subject to the general source material license (see Sect. 2.2.5.2), the facility's specific license application must demonstrate with reasonable assurance that possession, use, or transfer of the product or device is not likely to cause any individual user to receive a radiation dose in excess of 10% of the annual limits delineated in 10 CFR 20.1201(a), "Occupational Dose Limits for Adults."

2.2.5 Requirements and Issues Related to Depleted Uranium Product Use. Use of DU products must either be exempt from the requirement to obtain an NRC/Agreement State license or be covered by a general or specific source material license.

2.2.5.1 Exempt Uses. Use of DU products by DOE personnel and DOE contractors is exempt from the requirement to obtain an NRC/Agreement State source material license (10 CFR 40.11). Also exempt is use of the following DU products by persons who comply with specified conditions:

- Counterweights installed in aircraft, rockets, projectiles, and missiles [10 CFR 40.13(c)(5)]
- Metal shielding components of any shipping container [10 CFR 40.13(c)(6)]
- Detector heads in fire detection devices [10 CFR 40.13(d)]

2.2.5.2 General Source Material License. Existing NRC and NRC Agreement State regulations grant a general source material license. Under the general license, DU can be used in industrial products or devices for the purpose of providing a concentrated mass in a small volume, as long as the products or devices are manufactured or initially transferred in accordance with a specific source material license and certain other conditions are met (10 CFR 40.25).

2.2.5.3 Specific Source Material License. A user of a DU product must apply to the NRC or an NRC Agreement State for a specific source material license, unless the product is either exempt or covered by the existing license.

2.2.6 Requirements and Issues Related to Disposal. In a decision announced on February 25, 2000, *Record of Decision for the Department of Energy's Waste Management Program: Treatment of Low-Level Waste and Mixed Low-Level Waste; Amendment of the Record of Decision for the Nevada Test Site*, the DOE decided to perform minimum treatment of LLW at all sites and continue, to the extent practical, disposal of on-site LLW at INEEL, LANL, ORR, and SRS. In addition, the DOE decided to make the Hanford Site and the NTS available to all DOE sites for LLW disposal [FR 2000].

DOE Order O 435.1, "Radioactive Waste Management," and its implementing manual, DOE M 435.1-1, govern disposal of DU and materials containing residual DU (*e.g.*, empty DUF_6 cylinders and calcium fluoride from the neutralization of gas waste streams) in DOE-controlled LLW disposal facilities. The manual explains that DOE-controlled LLW waste disposal facilities must have a radioactive waste management basis consisting of a performance assessment, composite analysis, disposal authorization statement, closure plan, waste acceptance requirements, and monitoring plan. The waste acceptance requirements contain certain minimum criteria which could preclude disposal of some chemical forms (*e.g.*, DUF_6) and some physical forms (*e.g.*, finely divided or powdered metal) of DU without special packaging and/or stabilization.

DOE M 435.1-1 prohibits disposal of DOE-generated LLW, including DU or materials containing residual DU (*e.g.*, calcium fluoride and empty DUF_6 cylinders), in non-DOE LLW disposal facilities, unless the responsible DOE Field Element Manager approves an exemption for use of non-DOE facilities based, in part, on a determination that DOE-controlled disposal capabilities are not practical or cost-effective. If disposal in an NRC- or NRC Agreement State–licensed LLW disposal facility is approved, such facilities are subject to 10 CFR Part 61, "Licensing Requirements for Land Disposal of Radioactive Wastes," or compatible state regulations. Title 10 CFR Part 61 requires a demonstration of compliance with specified performance objectives and technical standards. The NRC has determined that near-surface disposal facilities in wet locations are extremely unlikely to successfully make such a demonstration if they accept DU_3O_8 [NRC 1994]. Title10 CFR Part 61 also requires facilities to establish waste characteristic limitations that could preclude disposal of some chemical forms (*e.g.*, DUF_6) and some physical forms (*e.g.*, finely divided or powdered metal) of DU without special packaging and/or stabilization.

2.3 Institutional Influences on Roadmap Development

In addition to the regulatory requirements and issues discussed in Sect. 2.2, several institutional influences have affected the development of this roadmap. These influences included two decision documents recently issued by DOE, two memoranda of understanding signed jointly by DOE and USEC, the availability of beneficial uses for materials resulting from the conversion of DUF_6 to DU oxide or DU metal, and the acceptance by the public and industry of the products made from such materials. Each of these is briefly described below.

The “Record of Decision for Long-Term Management and Use of Depleted Uranium Hexafluoride” was issued in July 1999 [FR 1999]. The decision is, in part, to convert the DOE’s DUF_6 inventory to DU oxide, DU metal, or both. The *Final Plan for the Conversion of Depleted Uranium Hexafluoride*, submitted to Congress in July 1999 as required by the Public Law 105-204 [DOE 1999b], presents a timetable for beginning the conversion process by the fourth quarter of 2004. Therefore, this roadmap assumes that the conversion will take place as planned.

Two memoranda of understanding signed between DOE and USEC in May and June of 1998 [DOE/USEC 1998a, 1998b] have transferred or will transfer approximately 98,000 MT of DU in the form of DUF_6 in approximately 11,200 cylinders from USEC to DOE. As discussed in Sect. 2, this brings the total number of DUF_6 cylinders that fall under DOE’s responsibility for managing to approximately 57,700. Although it is conceivable that DOE’s inventory of DUF_6 may change in the future due to transfers between DOE and USEC, for the purposes of this exercise, it is assumed that the inventory will stay constant.

It is recognized that important elements in development and realization of potential uses of DU in products are public acceptance and industry interest. One concern is the risk associated with radiation dose from DU in industrial products during normal usage and following postulated accidents. Another concern is financial liability of companies that manufacture and use these products. Therefore, some effort to estimate the risks from potential products and to communicate such risks to the public and industry could facilitate use of DU conversion products.

2.4 Transport Regulations for DUF_6-Derived Materials

In accomplishing the DUF_6 disposition mission, multiple types of materials will require transport in the public domain. In addition to transporting DUF_6 from current storage locations to processing facilities, the materials arising from the processing of DUF_6 [including the primary fluorine product (e.g., anhydrous hydrogen fluoride, calcium fluoride), cut and crushed cylinders, and secondary wastes] may also require transport to user or disposal sites. In all cases, the packaging and transport of these materials will be governed by DOT and NRC regulations. The packaging and transport of the DUF_6 may pose some unique problems as described in Sect. 2.3.

Table 2.1. Estimated U.S. inventory of depleted uranium [a]

Form	Owner	Location	MT as elemental uranium		
UF_6					470,500
	DOE-NE			375,000	
		Paducah	230,000		
		Portsmouth	108,000		
		Oak Ridge	37,000		
	USEC			95,500	
		Paducah	73,300		
		Portsmouth	22,200		
UO_3					19,500
	DOE-EM			19,500	
		FEMP [b]	34		
		SRS	19,440		
		Other	~1		
U metal					~3,000
	DOE-EM			~3,000	
		FEMP [b]	1,860		
		RFETS	22		
		Other	>1,000		
UF_4, other [c]					~3,000
	DOE-EM			~3,000	
		FEMP [b]	1,910		
		SRS	~500		
		Other	>100		
Various [d]	Various	Various		<2,500	<2,500
Total					~500,000

[a]The components of this table are believed to represent a reasonably complete and accurate estimate of the entire U.S. inventory of purified depleted uranium.
[b]This material is in the process of being transferred to DOE-NE at Portsmouth.
[c]These forms, at various DOE sites, include UF_4, oxides other than UO_3, process residues, and solutions.
[d]These components, which are estimated to account for less than 0.5% of the total U.S. inventory, are those of (1) DOE-NNSA, (2) DoD, (3) licensed commercial users, and (4) returns expected from foreign licensees.

3. DISPOSITION PATHS FOR DEPLETED URANIUM AND ASSOCIATED MATERIALS

This section describes the overall approach to DU disposition and a specific set of paths for such disposition as a basis for evaluation of the paths and identification of the preferred paths. The evaluation process and results are discussed in Sect. 4.

The options that are available for DU disposition are shown in Fig. 3.1. Disposition begins with material from two sources. The first material source is the DUF_6 inventory containing approximately 470,000 MTU of DU; 225,000 MT of fluorine; 74,000 MT of steel; and 58 MT of nickel and Monel. The second material source is the 25,500 MTU of surplus DU in DOE's inventory that is not in the form of DUF_6.

The first step in disposition is to convert the DUF_6 to a stable form in a conversion plant. Anticipated products of this plant are:

- Depleted uranium in the form of tetrafluoride, oxide, metal, or a combination of these
- Emptied DUF_6 storage cylinders
- Fluorine in a usable or stable form such as liquid hydrofluoric acid, gaseous anhydrous HF, other fluorine compounds having a higher unit value (e.g., BF_3), or solid calcium difluoride

Other surplus DU is expected to require characterization and possibly treatment of some portions of the inventory to meet subsequent disposition requirements.

Disposition of DUF_6 conversion products plus the other surplus DU then proceeds according to one or a combination of two scenarios: direct disposal or beneficial uses. Direct disposal can be accomplished by following paths such as near-surface disposal of various chemical forms of DU, cutting the cylinders into pieces and disposing of the segments as LLW, and disposal of a stable fluorine compound as LLW. Direct disposal is the reference path for all except the fluorine-bearing product, where industrial use of hydrofluoric acid or anhydrous HF is established practice.

The second scenario involves beneficial use of DUF_6 conversion products plus other surplus DU to reduce the overall cost to the government for DU disposition or achieve other worthwhile goals. This scenario can be accomplished by following paths such as use of appropriate chemical forms of DU in various products (*e.g.*, spent fuel storage and shipping casks), reuse of cylinders or their components, or industrial use of fluorine-bearing products. Ultimately, most of the DU-bearing products that are beneficially used will require disposal. For most DU products, disposal will involve burial in near-surface facilities for LLW. Other DU products might be used in the potential spent fuel repository. It is possible that relatively small amounts of unique DU forms will be retained in long-term storage as a national resource reserve to meet unspecified future demand. Designation as a national resource material would generally be accorded to those materials that would be very difficult to replicate or where there are multiple users of a particular DU form to the point that a single custodian is not practical.

There are barriers to implementing many of the candidate paths, especially those involving beneficial use of DUF_6 conversion products or other surplus DU. These barriers may be technical, economic, or institutional (*i.e.*, policy, regulatory, legal). It is necessary to elucidate these barriers as a foundation for decisions on which path(s) should be followed and which should be abandoned. The first step in elucidating the barriers is to define candidate disposition paths for DUF_6 conversion products and other surplus DU. Based on an analysis of the existing literature and input from a diverse group of experts, a list of candidate disposition paths was developed for DUF_6, forms of DU other than DUF_6, the fluorine from DUF_6 conversion, and DUF_6 storage cylinders. Paths that would implement the disposal scenario are described in Table 3.1, and paths that would implement the beneficial use scenario are described in Table 3.2. The reference disposition paths for DUF_6 conversion products are conversion to a stable form and disposal of most of the DU, retention of relatively small amounts of DU in various chemical forms as a national resource reserve, disposal of steel cylinder segments, and industrial use of anhydrous HF or hydrofluoric acid. Other paths constitute alternatives that might offer cost savings or other benefits to DOE. These lists of candidate paths are believed to comprehensively represent presently conceived uses of the materials associated with DU disposition irrespective of the development status, feasibility, or potential of each use. It is expected that most paths will not be pursued further because of one or more technical, economic, or institutional factors that are considered in the evaluation process described in Sect. 4.

Table 3.1. Description of candidate disposition paths for direct disposal of products from DUF_6 conversion and DU other than DUF_6

Candidate path	Candidate path description
DEPLETED URANIUM HEXAFLUORIDE	
LLW Disposal Reference Path for Most DU	• Convert DUF_6 to a stable form such as tetrafluoride, oxide, or metal • Package DU form and include DU products at the end of their useful lives • Dispose of the DU packages and products via burial in an LLW disposal facility
Mined Cavity Disposal	• Convert DUF_6 to a stable form such as tetrafluoride, oxide, or metal • Package DU form, possibly with a matrix such as grout, and include DU products at the end of their useful lives • Dispose of the DU packages and products in a new or existing deep geologic facility
Salt Mine Disposal as DUF_6	• Dispose of DUF_6 cylinders in a deep salt mine, possibly with overpacks
Subsurface Engineered Vault Disposal	• Convert DUF_6 to a stable form such as tetrafluoride, oxide, or metal • Package DU form, possibly with a matrix such as grout, and include DU products at the end of their useful lives • Dispose of the DU packages and products in subsurface concrete vaults
DU OTHER THAN DUF_6	
LLW Disposal of other DU Reference Path	• Characterize, convert, and package the DU other than DUF_6 to the minimum extent possible to meet WAC • Dispose of the DU as LLW
FLUORINE PRODUCTS	
Disposal of Fluorine	• Convert fluorine to CaF_2 or MgF_2 • Dispose of fluorine compounds
DUF_6 STORAGE CYLINDERS	
Dispose of Metals Reference Path	• Remove UF_6 • Wash cylinder internally • Reduce volume by sectioning and flattening • Send metal to a LLW disposal facility

Table 3.2 Description of candidate disposition paths for beneficial use of products from DUF_6 conversion and DU other than DUF_6

Candidate path	Candidate path description
DEPLETED URANIUM HEXAFLUORIDE	
DU MATRIX AND SHIELDING PRODUCTS	
Cement-Lock™	• Directly convert DUF_6 and other wastes to slag in a reactive melter • Quench molten material, grind with additives, and mix with cement to form high-density concrete • Form concrete into useful products • Eventually dispose of the products if feasible
DU Metal Shielding	• Convert DUF_6 to metal • Manufacture large metal shapes for use in shielding, primarily in spent fuel storage and transportation casks • Eventually dispose of the DU components
DUCRETE™	• Convert DUF_6 to oxide • Convert oxide to DU aggregate (DUAGG™) • Mix DUAGG™ with cement to make high-density concrete • Form high density-concrete into useful products such as spent fuel storage silos • Eventually dispose of products, possibly use as LLW packages
DUPoly	• Convert DUF_6 to oxide • Mix uranium oxide with molten polyethylene to form high-density polyethylene (DUPoly) • Form DUPoly into useful products such as shielding • Eventually dispose of products, possibly use as LLW packages
PYRUC	• Convert DUF_6 to oxide • Process DU oxide into small, sintered particles • Coat particles with a layer of pyrolytic carbon • Mix coated particles with cement to make high-density concrete • Form concrete into useful products such as spent fuel storage silos • Eventually dispose of products, possibly use as LLW packages
Uranium Silicide	• Convert DUF_6 directly into USi_X particles by reaction in molten silicon • Form particles into USi_X aggregate • Mix aggregate with cement to make high-density concrete • Form concrete into useful products such as spent fuel storage silos • Eventually dispose of products, possibly use as LLW packages
PROPOSED APPLICATIONS IN THE POTENTIAL REPOSITORY	
Backfill Component	• Convert DUF_6 to oxide • Mix DU oxide with rock and other additives at the potential repository site • Use the mixture to fill drifts containing spent fuel and waste packages at the time of closure • Backfill in emplacement drifts is not presently part of the reference design of the potential repository and is planned to be installed only in non-emplacement drifts. This may be re-evaluated in the future, but in any case backfill would not be installed any earlier than the 22nd century and maybe later.
Invert	• Convert DUF_6 to oxide • Make the DU oxide into particles or noncementitious DU aggregate • Insert DU form into cells formed by steel plates used to level the bottom of cylindrical tunnels in the potential repository • Inverts containing DU are not part of the reference design of the potential repository
Package Fill	• Convert DUF_6 to dioxide • Load spent fuel into waste package • Insert DU dioxide particles in all gas spaces inside the waste package but outside the fuel rods • Store and dispose of the packages in a repository • Package fill is not part of the reference potential repository design nor is it an alternative design option

Table 3.2 (cont'd)

Candidate path	Candidate path description
DEPLETED URANIUM HEXAFLUORIDE	
FISSILE MATERIAL DISPOSITION APPLICATIONS	
Ceramics for Pu Disposition	• Convert DUF_6 to dioxide • Mix DU dioxide with Pu dioxide and form a ceramic by sintering • Dispose of the ceramic in small cans within a larger can of defense HLW
Dilution of HEU	• Mix DUF_6 with $HEUF_6$ to yield LEU • Make LWR fuel • Dispose of spent fuel in the potential repository
MOX Fuel for Pu Disposition	• Convert DUF_6 to oxide • Mix DU oxide with Pu oxide and make LWR fuel • Use the fuel in a reactor • Dispose of spent fuel in the potential repository
COMMERCIAL APPLICATIONS [3]	
Aluminum-Refining Electrodes	• Convert DUF_6 to oxide • Mix DU oxide with other compounds and form electrodes • Use electrodes to refine Al from ores • Dispose of DU from electrode degradation with slag as industrial waste • Some DU is released as trace contamination in Al products
Catalyst for Fluid Cracking and to Promote Oxidation	• Convert DUF_6 to oxide • Combine with other materials to manufacture catalyst • Use catalyst to refine petroleum and process other chemicals • Dispose of spent catalyst as LLW or release as trace contaminants in products
Catalyst for Automotive Exhaust	• Convert DUF_6 to oxide • Combine with other materials to manufacture catalyst • Install catalyst in automobile catalytic converters • Recycle catalyst where possible; the excess will be disposed as LLW
Catalyst for Fuel Cells and Steam Reforming	• Convert DUF_6 to oxide • Combine with other materials to manufacture catalyst • Use catalyst to promote fuel cell reactions and steam decomposition to produce hydrogen • Dispose of spent catalyst as LLW
Heavy- Lifting- Vehicle Counterweight and High-Traction Devices	• Convert DUF_6 to metal • Form DU metal into large shapes • Use shapes as counterweights located under heavy-lifting equipment or locomotive wheels • Eventually dispose of the DU components as LLW
Oil Well Penetrators and Drilling Collars	• Convert DUF_6 to metal • Manufacture penetrators and drilling collars • Use charges deep underground to open strata and collars deep underground to stabilize drill bit • Use of penetrators constitutes disposal; collars would require disposal as LLW when not lost in the subsurface
NATIONAL RESOURCE RESERVE	
Long-Term Storage Reference Path for a Portion of the DU	• Decide how much of which DU forms should be part of the reserve • Convert DUF_6 to the desired form(s) and include other existing forms of DU as appropriate • Package DU form(s) • Store DU in a retrievable storage facility until it is used or a new decision declares it to not be needed

[3]Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.

Table 3.2 (cont'd)

Candidate path	Candidate path description
DEPLETED URANIUM HEXAFLUORIDE	
FUEL CYCLE APPLICATIONS	
AVLIS Reenrichment	• Convert DUF_6 to metal • Enrich DU metal to yield LEU • Make LWR fuel with product • Disposition remaining DU tails using one of the direct disposal or other beneficial use paths • Dispose of spent fuel in the potential repository
Fast Reactor Fuel	• Convert DUF_6 to dioxide • Mix DU dioxide with Pu dioxide to make fast reactor fuel and make U dioxide directly into blanket fuel • Recycle DU recovered from fuel reprocessing until it is consumed by transmutation and fission • Dispose of fission products in the potential repository as part of the high-level waste
SILEX Reenrichment	• Enrich DUF_6 without conversion to yield LEU • Make LWR fuel with product • Disposition remaining DU tails using one of the direct disposal or other beneficial use paths • Dispose of spent fuel in the potential repository
DU OTHER THAN DUF_6	
Reuse As Is	• Sell materials to NRC licensees "as-is" for less than the cost of disposal
Reuse with Further Processing	• Non-DUF_6 is processed by, or on behalf of, the government to desirable forms • DU materials are used by the government or sold to industry for commercial use subject to DOE policy on release of scrap metal
FLUORINE PRODUCTS	
Anhydrous and Aqueous HF for Industrial Use <u>Reference Path</u>	• Sell very slightly contaminated anhydrous and aqueous HF to industry for commercial use
Calcium Difluoride for Industrial Use	• Convert fluorine to CaF_2 • Sell very slightly contaminated CaF_2 to industry for commercial use
Elemental Fluorine for Industrial Use	• Sell very slightly contaminated elemental fluorine to industry for commercial use
High-Value Compounds for Industrial Use	• Convert fluorine to high-value compounds such as BF_3 or fluoropolymers • Sell very slightly contaminated high-value fluorine compounds to industry for commercial use
DUF_6 STORAGE CYLINDERS	
Decontaminate and Recycle Metals	• Remove UF_6 • Wash cylinder internally • Possibly perform more extensive decontamination, including surface cleaning or smelting • Sell slightly contaminated metals to industry for commercial use subject to DOE policy on release of scrap metal
Intact Cylinders as LLW Disposal Packages	• Remove UF_6 and convert • Refill cylinders with DU conversion product or some other LLW through opening cut in cylinder • Weld patch over fill opening • Store and dispose of refilled cylinders as LLW
Refabricate Metal for Use in Regulated Areas	• Remove UF_6 • Smelt steel and form shielding blocks or waste containers • Use slightly contaminated shielding blocks in radiologically regulated applications and eventually dispose of blocks • Fill waste containers and dispose as LLW

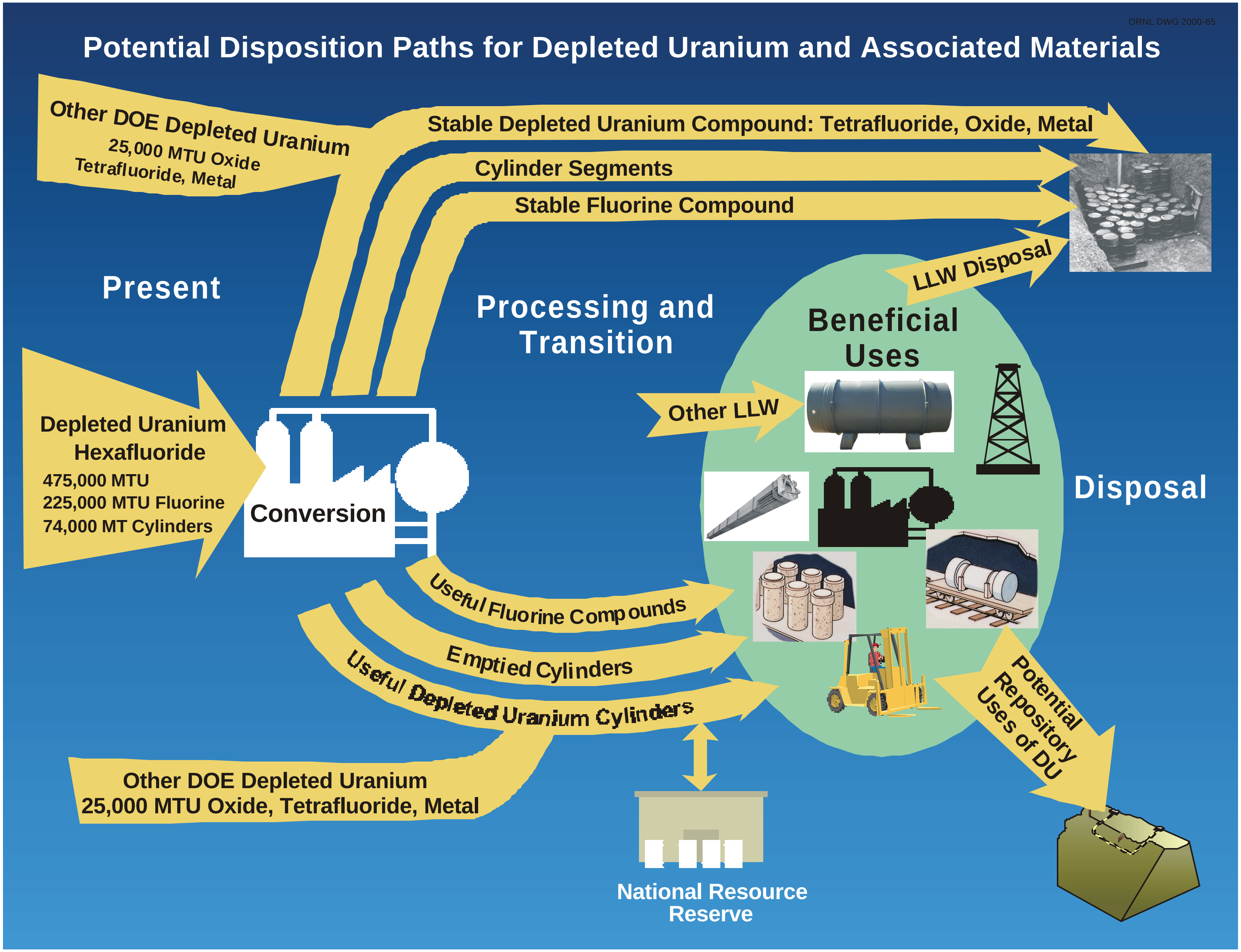

Fig. 3.1 Paths for disposition of surplus depleted uranium. Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.

4. EVALUATION OF CANDIDATE DISPOSITION PATHS

The purpose of this section is to provide a comparative analysis and evaluation of the candidate DUF_6 conversion product disposition paths identified in Sect. 3 for the purpose of determining which of the paths require further barrier reduction activities, whether such barrier-reduction activities are justified, and the relative priority of the activities. The approach used to accomplish this first involved establishing a set of criteria against which the paths would be evaluated, which is described in Sect. 4.1. Then, using a process described in Sect. 4.2, information related to the current status of each path was developed for each criterion and analyzed. The analysis results formed the basis for an evaluation of each path and assignment to one of four categories defined in Sect. 4.3. The category definition is based on whether the path should be pursued and, if so, the relative priority of the path.

4.1 Disposition Decision Criteria

This section defines the criteria against which the candidate disposition paths for DUF_6 conversion products are evaluated. These criteria are used to analyze whether further barrier-reduction activities are justified for a particular path and, if so, the relative priority of such activities.

4.1.1 Barrier Existence. This criterion relates to whether any barriers were identified for a particular path. If there are no barriers, the path could be pursued without technical or institutional impediment, and it was assigned to Category D. DOE's interest is then reduced to ensuring that adequate supplies of the proper form of DU are available to allow the path to be implemented. Potential responses to this criterion were that barrier reduction is required or barrier reduction is not required. If barriers do exist, the relative priority of additional barrier-reduction activities is analyzed by considering the other criteria.

4.1.2 Utilization of Depleted Uranium. This criterion addresses the extent to which a particular DU disposition path could result in net consumption of the DU inventory over 20 years, which, in turn, provides justification for investing in barrier-reduction activities related to that path. The basis for this criterion is that the cost of barrier-reduction activities must be allocated to each unit of product, and a small number of product units would likely result in an unacceptably high product cost even if the product were otherwise economic.

4.1.3 Economics. This criterion reflects the potential for a particular disposition path to result in net cost savings as compared with a reference path. The reference path is taken to be conversion of the DU to a stable form followed by disposal at a site where large amounts of DU would be acceptable in the near surface without need for a waste form matrix such as grout. The reference path for fluorine is industrial use as lower-value compounds (*e.g.*, HF, CaF_2). The reference path for cylinder disposition is volume reduction and disposal as LLW. Consideration of *net* cost savings is intended to recognize the fact that some paths may involve increased cost to one part of DOE while reducing costs in another part of DOE.

4.1.4 Other Impacts. This criterion encompasses the extent to which beneficial use of DU might improve or degrade some aspect of programs that are relevant to DOE, but where the impact is not reflected in cost. Examples might be a change in occupational or public health risk, or better reliability, performance, or predictability of some activity.

4.1.5 Technical Maturity. This criterion reflects the likelihood that an investment in the technical aspects of development for a particular path would eventually lead to a deployable technology. It includes consideration of the current status, feasibility of the projected technical requirements, and likelihood of success.

4.1.6 Institutional Challenges. This criterion is similar to that for technical feasibility, but addresses the likelihood that an investment to modify policy, regulatory, and legal barriers to a particular path is likely to be successful and allow a particular disposition path to be deployed.

4.2 Analysis and Evaluation Process for Disposition Paths

The process that was used to analyze and evaluate the potential disposition paths for DU is summarized as follows:

- Background information on specific topics was collected and organized by researchers at five national laboratories (Argonne National Laboratory, Idaho National Engineering and Environmental Laboratory, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory) that had extensive experience in specific aspects of DU disposition as a result of prior programmatic involvements.

- The contributions of individual researchers were consolidated into a draft report and circulated to all involved researchers plus multiple parts of DOE (Nuclear Energy, Environmental Management, Civilian Radioactive Waste Management) for round-robin review. The resulting background information is summarized in Sects. 2 and 3.

- The researchers plus representatives of all relevant DOE organizations convened in a workshop. The workshop involved two major activities: (a) presentation and analysis of the background information developed by each researcher to the entire workshop attendance and (b) assigning the potential DU disposition paths to one of the four categories based on the criteria described in Sect. 4.1. Each path was assigned to a category using the following methodology:
  - Each attender independently assigned each path to one of the four following categories:
    - A. Further barrier-reduction activities recommended
    - B. Further barrier-reduction activities should be considered
    - C. Further barrier-reduction not recommended
    - D. No additional Federal barrier-reduction activities needed
  - The assignments were tallied, the paths provisionally assigned to one of the four groups, and these results shared with the entire group.
  - The resulting recommendations were discussed, modified slightly, and adopted by consensus.

- The results of the workshop are documented as the remainder of this report, which was reviewed by the workshop attendees as well as other elements of DOE.

The results of analyzing the background information is summarized in Appendix A for the disposal (Table A.1) and beneficial use (Table A.2) paths. The recommended category assignments of each path are described in the following section and the tables associated with it.

4.3 Recommended Categorization of Disposition Paths

The information summarized in Appendix A was used by the workshop attenders to evaluate the disposition paths for DU-related materials and to assign them to one of the four categories using the process summarized in Sect. 4.2. The results of this evaluation and the associated explanation are summarized in the following sections, which correspond to the four categories. Within each category the disposition paths are presented in alphabetical order.

4.3.1 Category A: Barrier Reduction Recommended. The disposition paths assigned to Category A are the most promising of all the paths considered or constitute a reference approach that could be reliably implemented. In general, the beneficial use disposition paths in this category could use the majority of the DU, have good potential to yield net system wide cost savings relative to the reference case or other benefits that justify their cost, and are judged to have barriers that are likely to be overcome in a straightforward manner.

The roadmap workshop concluded that barrier-reduction activities in Category A should be immediately funded at a level sufficient to bring them to the point where they can be reliably deployed. The paths in this category and an explanation for their inclusion are summarized in Table 4.1.

Table 4.1 Category A: Disposition paths for which barrier-reduction activities are recommended

Path	Explanation
DEPLETED URANIUM HEXAFLUORIDE	
LLW Disposal	• <u>Reference</u> disposition path for all DU not beneficially used • Substantial post-conversion cost for disposal of unconsolidated packaged DU at a DOE site • Establishing DU-specific requirements to meet the WAC, negotiating terms and conditions, and possible integration with long-term storage are barriers to be reduced
Long-Term Storage	• <u>Reference</u> path needed to maintain limited amounts of unique forms of DU as a national resource • Desirable contingency in case other disposition options are delayed • Net cost that grows with the length of storage • Barrier-reduction activities should focus on ensuring long-term package integrity and operating efficiencies such as relying on recovery from a disposal site in the case of an urgent national need
Heavy Concrete	• Focus on uses such as radiation shielding and spent nuclear fuel / HLW transportation and storage. • Use of DU-based heavy concrete is prohibited in the potential repository because cementitious matrices might adversely affect water chemistry, waste package corrosion, and radionuclide migration • Significant previous development; barrier reduction appears straightforward • Potential for net system cost savings by deferring DU disposal and end-of-life use as an LLW package
DU OTHER THAN DUF_6	
LLW Disposal	• <u>Reference</u> path for all DU other than DUF_6 that is not used for beneficial purposes • Can accommodate all of the non-DUF_6 inventory • This should be pursued in case the private sector cannot, or will not, absorb all of this inventory • Barrier-reduction activities should be limited and focused on meeting WAC at DOE disposal sites
DUF_6 STORAGE CYLINDERS	
Intact Cylinders as LLW Disposal Packages	• <u>Reference</u> path for disposition of all cylinders except those having sufficiently impaired integrity • Has been studied, and barriers are minimal • Significant net savings as compared with cylinder disposal and other cylinder disposition options

4.3.2 Category B: Further Barrier Reduction Should Be Considered. The disposition paths assigned to Category B have some promise of being justifiable based on cost or other improvements. Most of these can also use a significant portion of the DU inventory. However, compared with Category A paths, these paths suffer from some combination of a lower probability of yielding net system wide cost savings or other benefits and being able to overcome successfully their respective barriers. In particular, many of these paths would involve use of significant amounts of DU outside of radiologically regulated areas. Such paths face regulatory uncertainties and issues of risk perception that can present significant institutional barriers. Previous attempts to overcome similar barriers have been demonstrably unsuccessful (*e.g.*, NRC's attempt to establish "Below Regulatory Concern" levels for releasing materials containing minuscule amounts of radioactivity to unregulated disposal facilities). Earlier this year, in response to concerns about the release of volumetrically contaminated nickel from the East Tennessee Technology Park, the Secretary of Energy established a moratorium prohibiting the release of all volumetrically contaminated metals from DOE facilities to give the NRC time to develop national standards for volumetrically contaminated materials, allow the public to weigh in on the development of a national policy, and allow DOE to establish its moratorium policy, directives, and guidance in this regard. In addition, on July 13, 2000, DOE Secretary Richardson suspended the unrestricted release for recycling of scrap metals from radiation areas within DOE facilities. This suspension is to remain in effect until DOE implements improved release criteria and information management requirements relating to these materials. The impact of these activities and decisions on potential use of fluorine products years hence is unknown.

DOE should selectively consider investing in the DU disposition paths in Category B based on judgments concerning the relative merits of specific proposals and the availability of funds.

Table 4.2 Category B: Disposition paths for which barrier-reduction activities should be considered

Path	Explanation
DEPLETED URANIUM HEXAFLUORIDE	
Aluminum-Refining Electrodes	• Can use up to 100% of the DU inventory as oxide in an industrial environment, but with potential for trace amounts of DU in aluminum products and slag waste • Significant technical issues need to be addressed, especially the rate at which DU oxide electrodes dissolve in the aluminum product and slag • Limited generic barrier-reduction activities to define the specific regulatory framework applicable to use of this product, evaluate degradation rates and performance, and provide key data on electrode solubility and performance
Catalyst for Fuel Cells and Steam Reforming	• Can use up to 50% of DU inventory as the oxide in an industrial environment or, conceivably, in consumer products (*e.g.*, small fuel cells for vehicles or homes) • Limited generic barrier-reduction activities to define the specific regulatory framework applicable to use of this product and limited investigation of catalytic performance
Catalyst for Automotive Exhaust	• Can use up to 50% of the DU inventory as the oxide in consumer products • Recovery and recycle of used converters is possible, but efficiency of recovery is uncertain • Limited generic barrier-reduction activities to define the specific regulatory framework applicable to use of this product and limited research on catalytic performance
Heavy-Lifting-Vehicle Counterweights and High-Traction Devices	• Can use up to 100% of the DU inventory as metal in an unregulated industrial environment • Higher cost of counterweights may be offset by warehouse cost reductions in the case of forklifts, which are a major potential application. Should also reduce forklift fatality frequency • Limited generic barrier-reduction activities to define the specific regulatory framework applicable to use of this product in unregulated areas
Invert	• Use of DU-based heavy concrete is prohibited in the potential repository because cementitious matrices may adversely affect water chemistry, waste package corrosion, and radionuclide migration • Consider limited investigation of inserting DU oxides in sealed cells formed by invert made of steel plate that could provide ballast and might enhance performance of the potential repository
Mined Cavity Disposal	• Could use up to 100% of the DU inventory • Significantly more expensive than near-surface disposal • Limited activities recommended to ascertain the terms and conditions for mined cavity DU disposal
Oil Well Penetrators and Drilling Collars	• Can use up to 50% of DU inventory as the metal • Some historical use in this application • Limited generic barrier-reduction activities to define the specific regulatory framework applicable to use of this product and limited evaluation of market conditions
Package Fill	• Net cost increase may be justified if the performance of the potential repository were to be improved • Further study would be needed before it can be determined if package fill would be beneficial or detrimental to the performance of the potential repository • Timing is an issue relative to an Environmental Impact Statement (EIS) and license application for the potential repository
Uranium Silicide	• Could use up to 100% of the DU inventory • One-step defluorination and conversion to a form potentially suitable as aggregate in heavy concrete or for disposal offers the possibility of a less costly, second-generation DUF_6 conversion process • Concept is presently theoretical, and significant R&D would be required for several years • Consider limited investment to elucidate chemistry

Table 4.2 (cont'd)

Path	Explanation
DU OTHER THAN DUF_6	
Reuse As Is	• No need for material within the DOE system • Amount of DU is relatively small (about 25,500 MTU), composed of multiple lots of different forms of DU with variable impurities that are not well-known • DOE does not have the capability to process this material without an investment that would not be cost-effective • Limited activities needed to (a) characterize materials so they can be beneficially reused over a period of years at a price that results in a net cost reduction and (b) examine liabilities of high-profile impurities such as Pu
FLUORINE PRODUCTS	
High-Value Fluorine Compounds for Industrial Use	• Can use up to 100% of fluorine • Use of very slightly uranium contaminated fluorine is regulated for users under present NRC regulations • Potential to yield larger revenues from fluorine by-product • Only at the concept stage; potential exists to flood small markets • Barrier-reduction activities need to focus on synergistic market analysis, flowsheet development, and enabling policy changes.

4.3.3 Category C: Further Barrier Reduction Not Recommended. The disposition paths assigned to Category C have limited promise of being justifiable compared with paths in Categories A and B. Most of these can use a significant portion of the DU inventory. However, these paths either have high fundamental barriers (*e.g.*, substantial technical impediments, conflict with U.S. laws or policies) or they perform the same function as other paths that are much more promising. There is little chance that additional work would make Category C disposal paths viable.

DOE should not invest in the paths in Category C for the purposes of DU material disposition.

Table 4.3 Category C: Disposition paths for which barrier-reduction activities are not recommended

Path	Explanation
DEPLETED URANIUM HEXAFLUORIDE	
AVLIS Reenrichment	• Net utilization is <5% of inventory • Requires significant increase in the cost of natural uranium for economic breakeven • U.S. AVLIS program has been terminated • Other laser-based processes are more promising because they can accept DUF_6 as feed
Cement-Lock™	• Process is primarily for treatment of hazardous organic chemical waste to yield a construction material • Flowsheet that can handle DUF_6 with the difficult fluorine by-product stream needs considerable development • The specific regulatory framework applicable to use of this product is not defined, but the general regulatory framework is not conducive to such use
DUPoly	• Potential for combustion and radiolytic hydrogen production • Organic chemicals are prohibited in the potential repository • Costs significantly more than cement-based heavy concretes for the same function
Catalyst for Fluid Cracking and to Promote Oxidation	• Would use <1% of the inventory in an industrial environment with potential for traces of DU in products • Use is in an unregulated area
PYRUC	• Uses a complicated process designed to produce high-quality nuclear fuel to achieve the same result as less costly heavy concretes based on simple DU oxide aggregates
Salt Mine Disposal as DUF_6	• Has the potential to accommodate entire inventory without need for conversion • Chloride-based salt has potential to be relatively compatible with DUF_6 • Development of a new facility for this purpose could require new statutory authority and regulations, and is likely to be costly and contentious • Potential for reaction of DUF_6 with brine in salt beds
Subsurface Engineered Vault Disposal	• This type of facility could accommodate the entire inventory of DU • Such a facility is unique and more costly than near-surface disposal but offers few additional benefits
DU OTHER THAN DUF_6	
Reuse with Further Processing	• Would require refurbishment and restart of closed DOE facilities • Small amount of material would result in a unit cost likely to be much larger than the cost of disposal
DUF_6 STORAGE CYLINDERS	
Decontaminate and Recycle Metals	• Much more costly than other alternatives • Exception is the small amount of Monel in cylinder valves, which is presently being recovered using existing processes

4.3.4 Category D: No Barrier Reduction Requiring Federal Action Needed. The disposition paths assigned to Category D have merit but also have attributes that make barrier-reduction activities currently undesirable. This situation occurs for a number of reasons:

- The potential use is laudable but is so far in the future that near-term investments cannot be justified.
- The potential use represents existing practice, and no further Federal investment for the purpose of supporting DU disposition is needed.
- The potential use is already being adequately supported.

DOE should monitor programs related to disposition paths that involve distant future demands and be prepared to consider investing in barrier-reduction activities if the demand is imminent. For uses involving existing practice or meeting the needs of ongoing programs, DOE should monitor these programs and be prepared to supply appropriate DU feed material from its inventory as required.

Table 4.4 Category D: Disposition paths for which further barrier-reduction activities are not needed

Path	Explanation
DEPLETED URANIUM HEXAFLUORIDE	
Backfill	• Could use up to 100% of the DU inventory • Decision on whether to use any backfill will not be made for decades and the need is yet further in the future • Such use may be worthwhile and should be considered when the backfill situation clarifies • Backfill in emplacement drifts is not presently part of the reference design of the potential repository and is planned to be installed only in non-emplacement drifts. This may be re-evaluated in the future, but in any case backfill would not be installed any earlier than the 22st century and maybe later
Ceramics for Pu Disposition	• DU will be used for this purpose, but the amount that might be used is <0.1% of the inventory • This use of DU is already being supported by DOE's Office of Fissile Material Disposition (DOE-MD) • DOE should be prepared to supply the required DU once the requirements are known
Dilution of HEU	• The amount that might be used is <5% of the inventory • The use of DU in this application is already being supported by DOE-MD • DOE should be prepared to supply the required DUF_6 once the precise specifications are known
DU Metal Shielding	• Use of DU metal in spent fuel casks and other applications is existing practice, and a number of such casks and other applications presently exist • DOE should be prepared to supply DU feed to the private sector as demand requires, but the amount of such demand is expected to be small
Fast Reactor Fuel	• This could consume the entire inventory of DU over many years • As a matter of policy, the United States is not supporting development of fast reactors, and such a program does not appear likely because of the low cost of natural uranium and concerns about the recycle of plutonium • DOE should reevaluate DU needs for fast reactors if such a program is considered in the future
MOX Fuel for Pu Disposition	• The amount that might be used is <1% of the inventory • Use of DU in this application is already being supported by DOE-MD • DOE should be prepared to supply the required DU once the requirements are known
SILEX Reenrichment	• Net utilization is <5% of inventory if all DU were reenriched • Claimed to have more potential than AVLIS or other atomic processes • Process is not well developed for uranium but is being supported by USEC • Requires increase in the cost of natural uranium for economic break-even ranging from slight for DU >0.4% ^{235}U to substantial for the bulk of the DU in the 0.2–0.3% range. • DOE should monitor developments and be prepared to supply higher-value tails if this process is deployed by others

Table 4.4 (cont'd)

Path	Explanation
FLUORINE PRODUCTS	
Anhydrous and Aqueous HF for Industrial Use	• Uranium concentrations are sufficiently low so that users of released material are not required to obtain an NRC license, but there may be some reluctance by the commercial sector in using these materials in non-nuclear applications until DOE's policy relating to the release of scrap metal is finalized. • HF is frequently recycled, although it calcium difluoride is sometimes the preferred product when it must be transported off-site
Calcium Difluoride for Industrial Use	• Uranium concentrations are sufficiently low so that users of released material are not required to obtain an NRC license, but present DOE policy prohibits release of such material and this could become permanent • Calcium difluoride is frequently recycled and is often the preferred product when it must be stored or transported off-site
Dispose of Fluorine	• This is established practice • Disposal of fluorine products from commercial defluorination of DUF_6 is uncommon because they have value
Elemental Fluorine for Industrial Use	• Uranium concentrations are sufficiently low so that users of released material are not required to obtain an NRC license • Fluorine is not an item in inter-site commerce because it is effectively untransportable in significant amounts
DUF_6 STORAGE CYLINDERS	
Dispose of Metals	• This is established practice because the cleaned cylinders can easily meet waste acceptance criteria at LLW disposal sites • This path is more costly than use of the cylinders as waste containers, but it might be justified under some circumstances (*e.g.*,. for cylinders that do not have integrity adequate for use as a WP)
Refabricate Metal for Use in Regulated Areas	• This is established practice because industry has made waste containers from recycled contaminated steel • The cost of smelting and refabrication is estimated to be greater than the value of the steel

4.4 Summary

The evaluation results discussed in Sect. 4.3 are summarized in Table 4.5 by category and material type.

Table 4.5 Summary of disposition path evaluation for products from DUF_6 conversion and DU other than DUF_6

Category A: Barrier-reduction activity recommended	Category B: Barrier-reduction activity should be considered	Category C: Barrier-reduction activity is not recommended	Category D: Barrier-reduction activity is not needed
DEPLETED URANIUM HEXAFLUORIDE			
• LLW disposal • Long-term storage • Heavy concrete	• Aluminum refining electrodes • Catalyst for fuel cells and steam reforming • Catalyst for automotive exhaust • Heavy-lifting-vehicle counterweights and high-traction devices • Invert • Mined cavity disposal • Oil well penetrators & drilling collars • Package fill • Uranium silicide	• AVLIS reenrichment • Cement-Lock™ • DUPoly • Catalyst for fluid cracking and to promote oxidation • PYRUC • Salt mine disposal as DUF_6 • Subsurface engineered vault disposal	• Backfill • Ceramics for Pu disposition • Dilution of HEU • DU metal shielding • Fast reactor fuel • MOX fuel for Pu disposition • SILEX reenrichment
DU OTHER THAN DUF_6			
• Reuse as is	• LLW disposal	• Reuse with further processing	
FLUORINE PRODUCTS			
	• High-value fluorine compounds for industrial use		• Anhydrous and aqueous HF for industrial use • Calcium difluoride for industrial use • Dispose of fluorine product • Elemental fluorine for industrial use
DUF_6 STORAGE CYLINDERS			
• Intact cylinders as LLW disposal packages		• Decontaminate and recycle metals	• Dispose of metals • Refabricate metal for use in regulated areas

5. RECOMMENDED DISPOSITION BARRIER-REDUCTION ACTIVITIES

Section 4 analyzed and evaluated a number of DU disposition paths leading to identification of paths that were recommended or should be considered for further development. The purpose of this section is to (a) present a consolidated list of barrier-reduction activities for these two groups, (b) indicate where specific activities would benefit multiple paths, and (c) identify major cross-cutting or systems issues that should be addressed. This section does not attempt to prioritize the activities, nor does it constitute a plan for implementing a DU disposition program.

5.1 Barrier-Reduction Activities to Support Recommended Paths

Barrier-reduction activities that are required to support the recommended (Category A) paths are summarized in Table 5.1. The major component of these activities would be a broad spectrum of activities to bring DU disposition paths involving heavy concrete and fill in packages destined for the potential repository to the point where these technologies could be deployed, if justified, by the increased knowledge obtained from the activities. Other paths for which barrier-reduction activities are recommended should involve targeted investments to address specific barriers.

Table 5.1 Category A: Barrier-reduction activities to support recommended paths

Path	Barrier-reduction activities
DEPLETED URANIUM HEXAFLUORIDE	
LLW Disposal	• Technical studies to support establishment of DU-specific requirements that meet WAC for disposal of DU oxide and tetrafluoride, and result in minimal DU disposition costs
Long-Term Storage	• Establish national resource reserve requirements for various forms of DU • Develop specifications for a long-term waste package (WP) for DU oxide, tetrafluoride, and metal • Limited systems studies to determine optimal long-term storage options (*e.g.*, disposal from which DU could be recovered if an urgent national need arose)
Heavy Concrete	• Measurement of thermal and mechanical properties of heavy concrete (*e.g.*, thermal conductivity, strength, and chemical stability) to be combined with specific cask designs in order to meet overall functional requirements necessary to obtain NRC approval of containers • Optimization and measurement of nuclear shielding properties (*e.g.*, direct measurements of shielding attenuation utilizing neutron and gamma sources, and use of materials containing boron and hydroxides) • Development of high-performance heavy concrete (*e.g.*, increase flexural strength, impact resistance, energy absorption, and fracture toughness; primarily to be achieved through addition of metal fibers) • Fabrication of prototype structures and samples, including development of preplaced aggregate and pumped grout • Further examine and modeling of oxidation processes of DU aggregate under conditions of elevated temperature and humidity when surrounded (and not surrounded) by the aluminosilicate grain boundary phase in the concrete matrix in order to predict stability over long periods of time • Optimize the process for producing the DU aggregate and the formulation of the heavy concrete • Facilitate manufacturer-purchaser relationships to establish a market for heavy concrete products
DU OTHER THAN DUF_6	
Reuse As Is	• Additional characterization of impurities to allow various lots of DU other than DUF_6 to be matched with potential users
DUF_6 STORAGE CYLINDERS	
Intact cylinders as LLW disposal packages	• Procedures for detecting substandard cylinders, filling cylinders, and sealing penetrations • Demonstration use of cylinders as a LLW package

5.2 Barrier Reduction Needed to Support Paths That Should Be Considered

Barrier-reduction activities that are required to support paths that should be considered (Category B) are summarized in Table 5.2. Investigating use of DU oxide in steel invert in the potential civilian repository would require a broad spectrum of work. Such an investigation can benefit from results that would be produced by barrier reduction activities concerning package-fill for the potential repository and heavy concrete. All other paths in this category should be considered for targeted investment to pursue specific issues, after which additional decisions on their worth would be required. In both cases, many activities benefit multiple projects, and these are discussed in the next section.

Table 5.2 Category B: Barrier-reduction activities to support paths that should be considered

Path	Barrier-reduction activities
DEPLETED URANIUM HEXAFLUORIDE	
Aluminum-Refining Electrodes	• A generic effort to define the framework applicable to DOE release and private sector use of DU (see Sect. 5.3) • Limited initial investment in the following to allow this option to be evaluated: - Determining the solubility and corrosion rate of UO_2 in the cryolite melt at 950E C - Establishing the electrical and mechanical properties of UO_2 -Cu composites
Catalyst for Automotive Exhaust Catalyst for Fuel Cells and Steam Reforming	• A generic effort to define the framework applicable to DOE release and private sector use of DU (see Sect. 5.3) • Limited initial investment in the following to allow this option to be evaluated: - Synthesis techniques for mesostructured uranium oxide catalysts - Measure catalyst activity - Thermal and mechanical stability of promising catalysts
Heavy-Lifting-Vehicle Counterweights and High-Traction Devices	• A generic effort to define the framework applicable to DOE release and private sector use of DU (see Sect. 5.3)
Invert	• *Uranium form*. The DU could be added as an oxide, silicate, or other chemical form. The preferred form to maximize invert performance per dollar invested must be determined • *Material compatibility*. The compatibility of the DU with the engineered barrier system must be demonstrated • *Ion-exchange capacity*. The WP-fill ion-exchange studies described earlier are also needed for invert applications. In addition, studies would be required to determine how much groundwater from the WP could realistically be expected to flow through the degraded invert with subsequent removal of the radionuclides • *Criticality*. Criticality studies are required to determine the degree of isotopic exchange between the invert and SNF uranium as groundwater flows through the degraded WP and invert • *Performance assessment*. An integrated model of WP performance with DU is required to demonstrate the impact of DU on system performance of the potential repository • *Economic analysis*. Cost-benefit analysis is required • *Legal and institutional analysis*. If DU were used in this application, it would presumably be a useful material— similar to the metal in the WP and thus legally may be treated like the WP materials of construction. However, it might also be considered a waste. An analysis of the issues associated with this possible duality is required
Mined Cavity Disposal	• Limited investment to pursue potential disposal in a mined cavity
Oil Well Penetrators and Drilling Collars	• A generic effort to define the framework applicable to DOE release and private sector use of DU (see Sect. 5.3) • Limited investment to achieve better understanding of the needs and barriers regarding this use of DU

Table 5.2 (cont'd)

Path	Barrier-reduction activities
Package Fill	• *Fill permeability*: Initial studies indicate that DU fill should lower the permeability of the WP to water and gas flow. Experiments and supporting models are required to (1) quantify this effect in terms of (a) maintaining chemical reducing conditions within the WP to prevent degradation of SNF and (b) minimizing water flow and subsequent transport of radionuclides from the WP and (2) analyze the effect of fill swelling on the SNF • *Ion-exchange capacity*. DU oxides may act as inorganic ion-exchange material that reduces release of radionuclides from the WP. This effect must be quantified—particularly for long-lived radionuclides that are important to performance of the potential repository • *Analogue Behavior.* Some natural UO_2 has remained intact under geological conditions similar to Yucca Mountain, Nevada, for several million years. A better understanding of the mechanisms (chemical reducing conditions, protective layers, etc.) is needed to provide licensing support that such a WP will minimize releases for very long time periods • *Criticality control.* DU lowers the average uranium enrichment of the WP below that required for nuclear criticality. Additional studies are required to confirm criticality control as the WP degrades and materials are transported from the WP • *WP and Fill Design*. If DUO_2 fill is used, the optimum WP and fill design to maximize performance and reduce costs may change. The incentives to change these components with a DU fill system must be evaluated • *Thermal Properties and Heat Transfer*. The replacement of the baseline fill gas within a WP with DU oxide particles will have an effect on heat transfer. Limited analytical studies based on very uncertain thermal data indicate that this is a small effect [Forsberg 1995]. The thermal properties of candidate fill materials need to be measured and used as input to sophisticated heat transfer modeling techniques that have been validated by benchmark experiments • *Radiation shielding*. The reduction in radiation emitted by the WP and its effects on operation and post-closure performance of the potential repository have not been investigated • *Emplacement technique*. The Canadians investigated many fill materials and their SNF has smaller clearances between fuel pins than does LWR SNF. However, DUO_2 particulate properties and LWR design features are somewhat different from their counterparts in the Canadian work, and, thus, confirmatory studies are required • *Optimization*. The preferred oxide and mix of particle sizes have not been investigated • *Performance assessment.* An integrated model of WP performance with DU is required to demonstrate the impact of DU on system performance of the potential repository • *Economic analysis*. A thorough analysis of the cost of using fill material is required • *Legal and institutional analysis.* If DU were used in this application, it would presumably be a useful material—similar to the metal in the WP and thus legally may be treated like the WP materials of construction. However, it might also be considered a waste. An analysis of the issues associated with this possible duality is required
Uranium Silicide	• Fundamental research on the chemistry of uranium silicide production, leading to proof-of-concept experiments involving the production of small amounts of aggregate • If successful, the entire suite of activities listed under heavy concrete in Table 5.1 must be undertaken
DU OTHER THAN DUF_6	
Disposal	• Additional characterization of impurities to establish acceptability for disposal
FLUORINE PRODUCTS	
Recycle High-Value Fluorine Compounds	• A generic effort to define the framework applicable to DOE release and private sector use of DU-contaminated material (see Sect. 5.3) • Studies of the chemistry of fluorine as it relates to producing potential high-value fluorine compounds such as BF_3, SF_6, fluoropolymers • Market studies to elucidate the preferred mix of higher-value fluorine products, potential impacts on the fluorine industry, and mechanisms for ameliorating the impacts • Assuming successful outcomes of the above, engineering development and demonstration of an integrated process for producing higher-value fluorine projects would be required

5.3 Cross-Cutting Barrier-Reduction Activities

Many of the DU disposition paths for which barrier-reduction activities are recommended or should be considered have common barrier-reduction needs in two areas. The first area includes activities that benefit multiple paths because the paths involve the same set of materials: DU, fluorine, and cylinders. The second area includes activities, typically called "systems studies," that are needed to design and optimize any program involving multiple components. Recommended barrier-reduction activities in these two areas were developed in the DU disposition workshop and are summarized below.

5.3.1 Barrier-Reduction Activities Supporting Multiple Paths. Barrier-reduction activities that could benefit multiple disposition paths for DU-related materials are as follows:

- Establishing the policy and regulatory framework for the extent and conditions under which DU-bearing products could be used in various non-governmental applications. This regulatory framework needs to be pursued in the context of concern over the trace amounts of some fission-product and transuranic elements potentially present in DUF_6 and consideration of rule making concerning release of contaminated solids by the NRC. Earlier this year, in response to concerns about the release of volumetrically contaminated nickel from the East Tennessee Technology Park, the Secretary of Energy established a moratorium prohibiting the release of all volumetrically contaminated metals from DOE facilities to give the NRC time to develop national standards for volumetrically contaminated materials, allow the public to weigh in on the development of a national policy, and allow DOE to establish its moratorium policy, directives, and guidance in this regard. In addition, on July 13, 2000, Department of Energy Secretary Richardson suspended the unrestricted release for recycling of scrap metals from radiation areas within DOE facilities. This suspension is to remain in effect until DOE implements improved release criteria and information management requirements relating to these materials.

- Establishing the framework of roles and responsibilities for DU use, including:
  - Responsibility for products made from DU-related materials
  - Regulatory responsibilities
  - Budget responsibilities
  - Market development and establishing incentive structures
  - Interfaces with other programs that might use DU

- Fostering public awareness of issues and benefits related to use of DU-bearing products[4]

5.3.2 Systemic Barrier-Reduction Activities. Barrier-reduction activities that are needed to establish the overall architecture of DU-related material disposition are as follows:

- Characterizing a reference disposition scenario for DU-related material disposition against which alternative disposition scenarios can be compared. These should cover everything between conversion and disposal and all surplus DOE DU and related materials.

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[4]Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.

- Conducting systems analysis and trade studies to identify preferred approaches for disposition of DU-related materials, and as a basis for allocation of costs and benefits.

5.4 Research Needed to Support Depleted Uranium Disposition

It is desirable to continue creating new knowledge leading to new uses of DU conversion products and to provide the scientific underpinning for known uses of these products. Topics relevant to the disposition of DU-related materials that could constitute topics for existing or supplemental mission-relevant research programs were developed in the DU disposition workshop and are as follows:

- Long-term interaction of DU oxides, metal, and tetrafluoride with container materials and the environment to support paths concerning package fill and invert for the potential repository, disposal, and long-term storage.

- Alteration of uranium oxides and tetrafluoride in aqueous or cement media over the long term to support paths concerning high-density concrete, fill and invert for the potential repository, and disposal.

- Processes for producing higher-value fluorine compounds that might reduce the cost of DUF_6 disposition.

- Direct conversion of DUF_6 to useful products (*e.g.*, DU conversion producing USi_x) that might reduce the total cost of conversion and disposition.

- Catalytic chemistry of DU oxides

- DU alloy science

A number of these topics could serve as a vehicle for investigating DU-related material disposition paths where limited investment to establish feasibility is indicated.

6. DOE'S APPROACH TO DEPLETED URANIUM MATERIAL DISPOSITION

Previous sections of this roadmap contain consensus recommendations concerning the depleted uranium disposition paths that might be worth pursuing and the barrier reduction activities that would be required for deployment to be possible. On this basis, the DOE has decided to pursue a prudent contingency approach to further research concerning disposition of DU materials. Specifically, the DOE plans on making investments in barrier reduction activities supporting the most promising paths involving beneficial use of DU materials while also making appropriate investments to ensure that economical disposal alternatives are reliably available and compatible with the potential uses. Those beneficial uses that are determined to be feasible, worthwhile, and acceptable will be implemented using the products of the DUF_6 conversion plants plus any acceptable DOE surplus inventory of other forms of DU. The DU-related materials that do not have clear beneficial uses will be destined for disposal. The DOE approach is further described in a 5-point plan described in the following paragraphs.

First, DOE will support a broad spectrum of investments to reduce barriers along paths related to nuclear material storage and/or disposal that have relatively low technical risk and use large quantities of DU in radiologically regulated areas. These paths have technical or institutional barriers that must be overcome before they can be fully evaluated or deployed. The areas of investment are summarized as follows:

- Heavy Concrete. To support economical manufacture of radiation shielding and spent fuel / nuclear waste storage casks (silos) from high-density concrete containing DU, DOE's barrier reduction activities will concentrate on characterizing and improving the potential for use of such products followed by disposal at the end of their useful life as LLW packages.
  - Technical activities: Characterize the thermal, shielding, structural, and chemical properties of high-density concretes to the point that the properties are well enough known to allow an NRC license to be obtained, and to inspire confidence in potential private sector or government purchasers. Optimization of processes and systems for manufacturing and using DU and high-density concrete casks will also be supported.
  - Institutional activities: Facilitating a mutually beneficial DU supplier-cask manufacturer-cask user relationship.
  - Presently, DU is not being used for SNF storage

- Package Fill. DOE will support activities focusing on characterizing the impacts of using DU oxide fill particles inside spent fuel disposal packages on the design and performance of the engineered barrier system to provide the basis for a subsequent decision as to whether such use is justified and, if so, how to license such use.
  - Technical Activities: The properties of DU oxide particle fill as they relate to heat transfer, chemical transformation, solubility, and interactions with other ions must be determined. Then, the impact of using this fill material on the engineering and risk-related performance of the engineered barrier system must be analyzed and compared with the reference design. Techniques for reliably inserting DU oxide fill into the waste package must be validated or modified. Optimization of the new waste package design would be required.
  - Institutional Activities: The use of DU filler in the potential repository must be evaluated. If after further development, DU oxide filler is found to be beneficial, mechanisms for amending the license application and/or additional NEPA analysis and documentation would have to be

determined at a later time. The Draft Yucca Mountain EIS does not address the use of DU as fill in the disposal packages.

- The current design of the potential repository does not include waste package fill

Second, DOE will make targeted investments to reduce barriers for a number of paths where there is potential to use substantial amounts of DU-related materials but where the uses are more speculative or simply require a small investment before the path could be followed.

- Use of DU in Non-Governmental Applications. This includes potential use of DU in forklift counterweights, catalysts, aluminum refining electrodes, metal alloys, and oil well penetrators and drilling collars. These paths share a common barrier because they involve use of DU in industrial or consumer settings.
  - Technical Activities: Limited investment in research is necessary to define the potential performance of these applications, to support institutional barrier reduction, and to provide a basis for subsequent decision making. These activities are captured in the fourth point of the plan.
  - Institutional Activities: While use of radioactive materials (*e.g.*, ^{241}Am in smoke detectors) in such applications already occurs, each such use must be approved by regulators. DOE will support an effort to establish the framework for use of DU in various types of applications to determine the extent to which such paths are institutionally feasible. As discussed in Sect. 2.2.3.2, DOE will also continue consideration of its policies concerning release of contaminated metals.

- Invert Containing DU. This path involves putting DU oxide into the cells of steel invert used to level the rounded bottom of tunnels in the potential repository to provide ballast and the possibility that the DU might improve the performance of the potential repository.
  - Technical Activities: Most technical activities required to support this path will be conducted under activities related to fill for the potential repository as described in the first point of the plan. Limited additional activities will be required to evaluate interactions of various forms of DU with carbon steel, establish the preferred form of the DU, and develop techniques for manufacturing invert containing DU.
  - Institutional: These issues will be addressed by activities conducted under the path concerning fill for the potential repository.
  - The current design of the potential repository does not include waste package fill

- Characterization of DOE's Non-DUF_6 Inventory. Potential paths for disposition of DOE's non-DUF_6 inventory are to sell the inventory for less than the cost of disposal, or, if this is not possible or desirable, to dispose of this material as LLW.
  - Technical Activities: DOE will invest in characterizing the contaminants in the 25,500 MTU of non-DUF_6 in its inventory, with emphasis on constituents that might impede use by NRC licensees or disposal, or which could represent an unacceptable liability to DOE or which could be contrary to DOE policy.
  - Institutional Activities: DOE will undertake efforts to research the market for disposition of the non-DUF_6 inventory at the highest possible cost and to provide assurance that disposal would not be impeded if it were to become necessary.

- Facilitating Use of Intact Cylinders as LLW Packages. The preferred path for disposition of DUF_6 storage cylinders is to use them intact as LLW packages by cutting an opening, loading them with LLW, welding a plug into the opening, and disposing of the package at a LLW disposal facility.
  - Institutional Activities: DOE will invest in establishing integrity and contamination criteria for use of cylinders as LLW packages and in developing procedures and interfaces to facilitate the use of cylinders as packages for disposal of DOE LLW.

Third, DOE will make appropriate investments to ensure that there are no barriers to following an optimal path for long-term storage or direct disposal of the DU conversion products that are not beneficially used or to disposal of DU-bearing products at the end of their useful lives.

- DU Disposal. To ensure availability of a reliable and economic disposal path for all DU-associated materials, DOE will undertake targeted technical and institutional activities.
  - Technical Activities: DOE will evaluate the performance (*e.g.*, risk, cost) of potential disposal facilities to support the institutional activities.
  - Institutional Activities: DOE will establish interfaces with appropriate disposal facilities to determine the requirements to meet their waste acceptance criteria and the cost for disposal of DU in LLW disposal facilities.

- Long-Term Storage. Long-term storage of some DU may be desired for the purpose of maintaining a national resource reserve or necessitated by impediments to other disposition paths.
  - Technical Activities: The optimal approach (*e.g.*, functional requirements, package design, facility design) for long-term storage of DU will be established. This approach will include consideration of allowing recovery of disposed DU to constitute the national resource reserve.
  - Institutional Activities: DOE will perform a detailed evaluation to determine the amount and form of the DU it wishes to maintain as a national resource reserve. This will be coordinated through the Office of Nuclear Material Management Policy.

Fourth, DOE will invest in basic and mission-directed research that is related to beneficial use of DU-related materials. These investigations are necessary to expand our knowledge of the basic properties of uranium that are necessary to provide a basis for evaluating the feasibility, impacts, and economics of potential DU disposition paths and to identify new beneficial uses of the DU conversion products. These research areas include the following:

- Long-term interaction of DU oxides, metal, and tetrafluoride with container materials and the environment to support paths concerning package fill and invert for the potential repository, disposal, and long-term storage.

- Alteration of uranium oxides and tetrafluoride in aqueous or cement media over the long term to support paths concerning high-density concrete, package fill and invert for the potential repository, and disposal.

- Processes for producing higher-value fluorine compounds that might reduce the cost of DUF_6 disposition.

- Direct conversion of DUF_6 to useful products (*e.g.*, DU conversion producing USi_x) that might reduce the total cost of conversion and disposition.

- Catalytic chemistry of DU oxides

- DU alloy science

Proposal solicitations will be structured to encourage new concepts that hold promise to economically use significant amounts of DU.

Fifth, DOE will invest in system analysis and support activities that benefit multiple aspects of DU material disposition.

- Establishing Institutional Roles and Responsibilities. DOE will facilitate establishment of the roles and responsibilities for funding, regulation, market development, incentive structures, and DU-related products and the interfaces between the elements having these responsibilities. This framework is necessary to effectively coordinate DU disposition activities that involve multiple DOE programs, regulators, and the private sector. Efforts to foster public acceptance of DU-bearing products will also be supported.

- System Optimization. DOE will characterize a reference system for DU-related material disposition against which alternative paths can be compared. This will then provide the basis for analyses to optimize the system.

DOE has initiated the preparation of a *Depleted Uranium Disposition Program Plan* that will detail the specific activities, and their associated budgets and schedules, that will be used to manage future R&D undertaken to implement the above approach.

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ACRONYMS

AHF	anhydrous hydrogen fluoride
AEA	Atomic Energy Act of 1954
ASME	American Society for Mechanical Engineers
ASTM	American Society for Testing and Materials
AVLIS	atomic vapor laser isotope separation
CFR	*Code of Federal Regulations*
DoD	Department of Defense
DOE	Department of Energy
DOE-DP	DOE Office of Defense Programs
DOE-EM	DOE Office of Environmental Management
DOE-MD	DOE Office of Fissile Materials Disposition
DOE-NE	DOE Office of Nuclear Energy, Science, and Technology
DOE-NNSA	DOE National Nuclear Security Agency
DOE-RW	DOE Office of Civilian Radioactive Waste Management
DOE-SC	DOE Office of Science
DOT	Department of Transportation
DU	depleted uranium
EIS	environmental impact statement
EPA	Environmental Protection Agency
EPACT	Energy Policy Act of 1992
FCC	fluid catalytic cracking
FEMP	Fernald Environmental Management Project
FMDP	Fissile Materials Disposition Program
FY	fiscal year
kg	kilograms
HEPA	high-efficiency particulate air (filter)
HEU(F)	highly enriched uranium (fuel)
HF	hydrogen fluoride (hydrofluoric acid)
INEEL	Idaho National Engineering and Environmental Laboratory
LEU	low-enriched uranium
LLW	low-level waste
LLRWPA	Low-Level Radioactive Waste Policy Amendments Act
LWR	light-water reactor
MOX	mixed oxide
MT	metric tons
MTU	metric tons of elemental uranium
NEPA	National Environmental Policy Act of 1969
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
RCRA	Resource Conservation and Recovery Act of 1976
RFETS	Rocky Flats Environmental Technology Site
SEU	slightly enriched uranium
SILEX	Separation of Isotopes by Laser Excitation
SNF	spent nuclear fuel
SRS	Savannah River Site
USEC	United States Enrichment Corporation

WAC	waste acceptance criteria
WIPP	Waste Isolation Pilot Plant
WP	Waste Package

APPENDIX A

ANALYSIS OF CANDIDATE DISPOSITION PATHS

Table A.1 Analysis of candidate disposition paths for direct disposal of products from DUF_6 conversion and DU other than DUF_6

Candidate Disposal Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
DEPLETED URANIUM HEXAFLUORIDE						
LLW Disposal <u>Reference Path for Most DU</u>	Yes; meeting specific WAC and lowering cost	Up to 100%	Relatively low cost	None unless coupled with long-term storage	Requires discussion with disposal site to establish optimal approach and costs	Potential environmental impacts and EIS
Mined Cavity Disposal	Yes; siting, legislation, and potential licensing	Up to 100%	Relatively high cost in a new facility, depending on the form of the DU; moderate cost in an existing facility	None	Requires siting, legislation, and potential licensing a new disposal facility	Potential environmental impacts and EIS
Salt Mine Disposal as DUF_6	Yes; interaction with salt, siting, legislation, and potential licensing	Up to 100%	Same as for a mined cavity, but the conversion cost would be avoided	Interaction of DUF_6 with halite and brine	Requires siting, legislation, and potential licensing a new disposal facility	Potential environmental impacts and EIS
Subsurface Engineered Vault Disposal	Yes; siting, legislation, and potential licensing	Up to 100%	Moderately low cost depending on the form of the DU	None	Requires siting, legislation, and potential licensing a new disposal facility	Potential environmental impacts and EIS
DU OTHER THAN DUF_6						
Beneficial Use Without Further Processing	Yes; some additional characterization of impurities	Up to 100%	Limited amount likely to have value to the private sector, and the avoided cost of disposal can be used as an incentive	Need to characterize potentially troublesome chemical and radioactive impurities	Impact of potential trace transuranic and fission-product impurities on use and liability	Potential environmental impacts and EIS
LLW Disposal <u>Reference Path</u>	Yes; additional characterization of impurities	Up to 100%	Selling material is likely to be more economical to avoid disposal cost, but disposal may be most economical path for impure material	Need to characterize potentially troublesome chemical and radioactive impurities	None	Potential environmental impacts and EIS

Table A.1 Analysis of candidate disposition paths for direct disposal of products from DUF_6 conversion and DU other than DUF_6 (cont'd)

Candidate Disposal Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
FLUORINE PRODUCTS						
Dispose of Fluorine	No; disposal of contaminated Ca or Mg difluoride is existing commercial practice	Up to 100%	Very small cost as long as DU concentration permits disposal in sanitary landfill	None	May be contrary to policy concerning release of volumetrically contaminated material to be established by DOE or NRC as applicable	Potential environmental impacts and EIS
DUF_6 STORAGE CYLINDERS						
Dispose of Metals <u>Reference Path</u>	No	Up to 100%	Moderate net cost; this is reference case	None	None	Potential environmental impacts and EIS

Table A.2 Analysis of candidate disposition paths for beneficial use of products from DUF_6 conversion and DU other than DUF_6

Candidate Beneficial Use Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
DEPLETED URANIUM HEXAFLUORIDE						
DU MATRIX AND SHIELDING PRODUCTS						
Cement-Lock™	Yes; no experience with DU materials	Up to 100%	Good potential for conversion and disposal cost to be less than cost of this complex, high-temperature process	Need proof-of-concept experiments, characterization of products, and measurement of properties	Use of a substantial amount of this product requires overcoming barriers to use in unregulated areas	Potential environmental impacts and EIS
DU Metal Shielding	No; existing practice	Up to 50%	DU metal is not presently cost-effective; unclear whether deferred disposal cost is enough to compensate	Mature technology, although there may be some benefits to establishing an ASME code section on DU metal so it could be used as a structural component	None	None
DUCRETE™	Yes; technical data, manufacturing techniques, user acceptance, and licensing	To be determined	Approximately equal to standard concrete storage silos on a system -wide basis, but with the possibility of further reductions after more development	Need to characterize properties, validate manufacturing techniques and long-term performance, produce demonstration casks, and optimize designs	Identify specific products and clarify NRC licensing requirements; gain acceptance from purchasers and manufacturers.	Environmental impacts. Can reduce dose during loading in situations that have previously required on-site transfer casks. Timing relative to license application for the potential repository.
DUPoly	Yes; made at laboratory scale	Up to 100%	Cost likely to be greater than cement-based products because of high cost of polyethylene	Need to improve leach resistance and clarify polyethylene stability issues; need economic modeling and costs estimates for shielding	Organic materials are not acceptable in the potential repository	Environmental impacts. Can reduce dose during loading in situations that have previously required on-site transfer casks
PYRUC	Yes; technology is in proposal stage	Up to 100%	Low potential due to high costs from complicated and expensive processing technologies	Need proof-of-concept experiments, optimization of sol-gel methods, fabrication of composites and product characterization.	Identify specific products and clarify NRC licensing requirements; gain acceptance from purchasers and manufacturers	Environmental impacts. Can reduce dose during loading in situations that have previously required on-site transfer casks
Uranium Silicide	Yes; technology is conceptual	Up to 100%	Some potential for eliminated conversion cost and deferred disposal cost to be less than cost of high-temperature process	Need proof-of-concept experiments, economic modeling, oxidation experiments, product characterization	Identify specific products and clarify NRC licensing requirements; gain acceptance from purchasers and manufacturers	Environmental impacts. Can reduce dose during loading in situations that have previously required on-site transfer casks

Table A.2 Analysis of candidate disposition paths for beneficial use of products from DUF_6 conversion and DU other than DUF_6 (cont'd)

Candidate Beneficial Use Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
APPLICATIONS IN THE POTENTIAL REPOSITORY						
Backfill Component	Yes; manufacture and use of DU oxide as a backfill component in the potential repository are not existing practice	To be determined	Trade-off of cost reduction from use constituting disposal against cost of storage until use occurs unlikely to be favorable	Need to understand how DU oxide interacts with groundwater and waste package	Obtain approval by DOE-RW and regulators for this application. Decision on whether to use backfill may not be made for decades.	Potential environmental impacts and EIS. May lower long-term risk at the cost of some increased risk during emplacement
Invert	Yes; manufacture and use of DU oxide for invert in the potential repository are not existing practice.	To be determined	Constitutes disposal; net cost of emplacement in the potential repository likely to be higher than disposal as LLW	Need to understand interactions with steel plate used in invert, groundwater, and waste package	Obtain approval by DOE-RW and regulators for this application. May need additional NEPA documentation and licensing actions because it is out of sequence with design and licensing process.	Timing an issue relative to the license application for the potential repository May lower long-term risk at the cost of some increased risk during emplacement and operations
Package Fill	Yes; manufacture and use of DU oxide to fill packages in the potential repository are not existing practice.	To be determined	Near-term cost addition for potential improvement; more speculative potential to eliminate other engineered barriers in the late 22nd century	Large-scale prototype work on waste package fill in Canada; need to characterize fill, develop insertion technology, determine impacts on package and the performance of the potential repository	Obtain approval by DOE-RW and regulators for this application. May need additional NEPA documentation and licensing actions because it is out of sequence with design and licensing process.	Timing an issue relative to the license application for the potential repository. May lower long-term risk at the cost of some increased risk during filling
FISSILE MATERIAL DISPOSITION APPLICATIONS						
Ceramics for Pu Disposition	No; development under way by DOE-MD	< 0.1%	Could use available DU dioxide or trioxide at low cost while eliminating disposal cost	Only bench-top demonstration so far	Unclear whether small cans of Pu/DU oxide ceramic in a large canister of HLW will provide adequate protection	None
Dilution of HEU	No; needed studies are being supported by DOE-MD	1–5%	Eliminates conversion and disposal cost, but for a small amount	None	None	None
MOX Fuel for Pu Disposition	No; development under way by DOE-MD	< 1%	Eliminates disposal cost, but for a small amount	Some development on pit alloying constituents	About 130 cylinders of DUF_6 have been set aside at Portsmouth for this purpose	None

Table A.2 Analysis of candidate disposition paths for beneficial use of products from DUF_6 conversion and DU other than DUF_6 (cont'd)

Candidate Beneficial Use Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
FUEL CYCLE APPLICATIONS						
AVLIS Reenrichment	Yes; AVLIS has only been demonstrated at laboratory scale	1- 5%	Not competitive until natural U price increases slightly for 0.4% DU; much more for bulk of DU that has lower enrichments	Complete demonstration of AVLIS technology	AVLIS Program has been discontinued	Potential environmental impacts and EIS
Fast Reactor Fuel	No; existing technology	Up to 100%	Fast reactors not economic without a major increase in uranium costs	None	Presidential Decision Directive 13 prohibits reprocessing; public acceptance of plutonium recycle	Potential environmental impacts and EIS. Fast reactors constitute a long-term, secure energy supply
SILEX Reenrichment	No; technology not proven but being supported by USEC	1- 5%	Not competitive until natural U price increases slightly for 0.4% DU; much more for bulk of DU that has lower enrichments	Can use DUF_6 without conversion, but still in research stage	SILEX is being supported using industry funding. Not a government program, and licensing is expected to be straightforward.	Potential environmental impacts and EIS
COMMERCIAL APPLICATIONS						
Aluminum-Refining Electrodes	Yes; use of DU in this application is not existing practice	Up to 100%	Estimates indicate that DU oxide electrodes could increase operating efficiency equivalent to DU having worth much greater than its cost	Virtually no work on this application; need solubility and degradation rate of electrodes and information on efficiency	Regulatory framework for use of electrodes and products has not been defined and may not be conducive to use	Potential environmental impacts and EIS
Catalyst for Fluid-Cracking and to Promote Oxidation	Yes; use of DU as a commercial catalyst is not established practice	< 1%	Unknown	Performance and degradation rates	Regulatory framework for use of electrodes and products has not been defined and may not be conducive to use	Potential environmental impacts and EIS
Catalyst for Automotive Exhaust	Yes; use of DU in automobiles is not established practice	Up to 50%	Unknown	Performance and degradation rates	Regulatory framework for use of electrodes and products has not been defined and may not be conducive to use	Potential environmental impacts and EIS

Table A.2 Analysis of candidate disposition paths for beneficial use of products from DUF_6 conversion and DU other than DUF_6 (cont'd)

Candidate Beneficial Use Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
Catalyst for Fuel Cells and Steam Reforming	Yes; use of DU as a commercial catalyst is not established practice.	Up to 50%	Unknown	Performance and degradation rates	Regulatory framework for use of electrodes and products has not been defined and may not be conducive to use	Potential environmental impacts and EIS
Heavy-Lifting-Vehicle Counterweights and High-Traction Devices	Yes; manufacture of equipment with DU components is not established practice	Up to 100%	DU products are more costly; however, warehouses can be less costly and locomotives with DU wheels can haul more payload	Prototyping and demonstration needed	Regulatory: worker exposure, ability to maintain control of counterweights	Potential environmental impacts and EIS. Can reduce forklift accidents, of which 90,000 occur each year with 85 fatalities
Oil Well Penetrators and Drilling Collars	Yes; DU has been used down-well in the petroleum industry, but market impediments are apparent	Up to 50%	Improved performance would have to compensate for the additional cost to produce DU metal	None	Regulatory framework for use of electrodes and products has not been defined and may not be conducive to use	Potential environmental impacts and EIS. Density of DU metal may improve drilling efficiency; increased dose to oil well workers
NATIONAL RESOURCE RESERVE						
Long-Term Storage <u>Reference Path for a Portion of the DU</u>	Yes; no previous experience with low-maintenance storage of relatively large quantities for decades	<10% of the inventory in a variety of forms having unique characteristics	A significant cost that may be minimized if potential exhumation of DU LLW is acceptable for this purpose	Need to develop concept and package specifications that minimize cost; establishing detailed strategic reserve requirements	Public, local governments, and some regulators object to long-term storage without definable use in sight	Potential environmental impacts and EIS

Table A.2 Analysis of candidate disposition paths for beneficial use of products from DUF_6 conversion and DU other than DUF_6 (cont'd)

Candidate Beneficial Use Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
DU OTHER THAN DUF_6						
Reuse As Is	Yes; some additional characterization of impurities	Up to 100%	Limited amount likely to have value to the private sector, and the avoided cost of disposal can be used as an incentive	Need to characterize potentially troublesome chemical and radioactive impurities	Potential impact of trace transuranic and fission-product impurities on use and liability	Potential environmental impacts and EIS
Reuse with Further Processing	Yes; technology exists but operational DOE facilities to further process the DU into useful forms do not	Up to 100%	Selling unprocessed DU to private sector likely to be more economical than processing this small amount of material	Would need to reactivate or establish facilities for processing; need to characterize potentially troublesome chemical and radioactive impurities	None	Potential environmental impacts and EIS
Disposal	Yes; additional characterization of impurities	Up to 100%	Selling material is likely to be more economical to avoid disposal cost, but this may be most economical path for impure material	Need to characterize potentially troublesome chemical and radioactive impurities	None	Potential environmental impacts and EIS

Table A.2 Analysis of candidate disposition paths for beneficial use of products from DUF_6 conversion and DU other than DUF_6 (cont'd)

Candidate Beneficial Use Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
FLUORINE PRODUCTS						
Anhydrous and Aqueous HF for Industrial Use Reference Path	No; these materials are produced and used commercially	Up to 100%	HF from uranium defluorination being sold or reused now in industry—could supply about 5% of U.S. demand	None	May be contrary to policy concerning release of volumetrically contaminated material to be established by DOE or NRC as applicable	Potential environmental impacts and EIS
Calcium Difluoride for Industrial Use	No; these materials are produced and used commercially	Up to 100%	HF from uranium conversion being sold or reused now in industry — could supply about 5% of U.S. demand	None; easier to store and transport than HF	May be contrary to policy concerning release of volumetrically contaminated material to be established by DOE or NRC as applicable	Potential environmental impacts and EIS
Elemental Fluorine for Industrial Use	No; production of elemental fluorine from HF is established technology	Up to 50%; use is limited because F_2 is not transportable and only used when absolutely required	Could command higher price than anhydrous hydrogen fluoride; this source (about 13,000 MT/y) is two-thirds of the worldwide demand	None	Regulations limit the amount that can be transported; significant quantities must be used at production site. May be contrary to policy concerning release of volumetrically contaminated material to be established by DOE or NRC as applicable	Potential environmental impacts and EIS
High-Value Fluorine Compounds for Industrial Use	Yes; production of F-containing compounds other than HF and CaF_2 is not existing practice	Up to 100%	High-value fluorine compounds sell for much more than HF but cost more to make; overproduction could lower prices and impact the private sector	Develop technology to produce a suite of high-value compounds	Reaction of private sector to the potentially detrimental intrusion into their market. May be contrary to policy concerning release of volumetrically contaminated material to be established by DOE or NRC as applicable	Potential environmental impacts and EIS

Table A.2 Analysis of candidate disposition paths for beneficial use of products from DUF_6 conversion and DU other than DUF_6 (cont'd)

Candidate Beneficial Use Path	Is additional barrier-reduction needed?	Inventory utilization	Net cost savings	Technical maturity and barriers	Institutional, legal, regulatory, and policy challenges and barriers	Other impacts
DUF_6 STORAGE CYLINDERS						
Decontaminate and Recycle Metals[a]	Yes; related to potential use of slightly contaminated metals in non-governmental applications	Up to 100%	About the same as direct disposal cost. Monel and nickel are being recycled, but cost of smelting steel outweighs value plus avoided disposal cost	None	Release is currently prohibited pending further NRC and DOE decisions.	Potential environmental impacts and EIS
Intact Cylinders as LLW Disposal Packages	Yes; procedures for cylinder reuse and loading	Approaching 100%. Some cylinders are in poor shape and would require disposal	Moderate net cost savings from avoided purchase of LLW packages plus avoided cylinders disposal cost	None	Need procedures to qualify, load, and seal cylinders	Potential environmental impacts and EIS
Refabricate Metal for Use in Regulated Areas[a]	No; refabrication of slightly contaminated metal is established practice	Up to 100% as LLW packages	Relatively low net cost savings compared to direct disposal from avoided purchases plus avoided cylinder disposal, less smelting and refabrication costs	None	None	Potential environmental impacts and EIS

[a] Reuse of storage cylinders may be subject to the Secretary of Energy's memorandum of July 13, 2000, suspending unrestricted release of contaminated metals from radiation areas.